



# Measurement of the $Z/\gamma^*$ ( $\rightarrow e^+e^-$ ) + $\geq n$ Jet Production Cross Sections in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

# Overview

- Theory Introduction and Motivation
- Experimental Apparatus
- Data and Monte Carlo Samples
- Measurement of the  $Z/\gamma^*$  ( $\rightarrow e^+e^-$ ) +  $\geq n$  Jet Cross Sections
- Systematic Uncertainties
- Results and Conclusions





# Theory Introduction and Motivation

# Introduction to the Standard Model (1)



The Standard Model (SM) of particle physics is the current theory of elementary particles along with the interactions that act between them (except gravity).

FERMIONS		matter constituents spin = 1/2, 3/2, 5/2, ...			
Leptons spin = 1/2		Quarks spin = 1/2			
Flavor	Mass GeV/c <sup>2</sup>	Electric charge	Flavor	Approx. Mass GeV/c <sup>2</sup>	Electric charge
$\nu_e$ electron neutrino	<1×10 <sup>-8</sup>	0	u up	0.003	2/3
e electron	0.000511	-1	d down	0.006	-1/3
$\nu_\mu$ muon neutrino	<0.0002	0	c charm	1.3	2/3
$\mu$ muon	0.106	-1	s strange	0.1	-1/3
$\nu_\tau$ tau neutrino	<0.02	0	t top	175	2/3
$\tau$ tau	1.7771	-1	b bottom	4.3	-1/3

- Quarks and Leptons are arranged in 3 generations
- Quarks are never observed as single particles
- Ordinary matter = electrons,  $u$  and  $d$  quarks
- Neutrinos interact weakly with matter

# Introduction to the Standard Model (2)

*Interactions are dictated by symmetry principles.*

## PROPERTIES OF THE INTERACTIONS

Property	Interaction	Weak (Electroweak)			Strong		Residual See Residual Strong Interaction Note
		Gravitational	Mass – Energy	Flavor	Electric Charge	Color Charge	
Act on:	All		Quarks, Leptons		Electrically charged	Quarks, Gluons	Hadrons
Particles experiencing:	Graviton (not yet observed)	$W^+$	$W^-$	$Z^0$	$\gamma$	Gluons	Mesons
Particles mediating:	Strength relative to electromag for two u quarks at: $3 \times 10^{-17}$ m	$10^{-41}$	$10^{-41}$	$10^{-7}$	0.8	1	25
	for two protons in nucleus					1	60
						Not applicable to hadrons	Not applicable to quarks
							20

- Quantum Mechanics + Special Relativity = Quantum Field Theory (QFT)
- Imposing symmetry conditions on quantum fields gives rise to mediating gauge bosons
- No QFT for gravity has been experimentally established yet



# Electromagnetic Interaction

- *Quantum Electro Dynamics (QED) is the QFT describing the EM interaction*
- The mediating gauge boson is the *massless photon ( $\gamma$ )*
- Since  $\gamma$  is *massless*, the interaction has infinite range
- The strength of the EM interaction is proportional to the *fine structure constant*:

$$\alpha_{\text{EM}} \approx 1/137$$



# Electroweak Interaction

- A QFT combining EM with weak interaction exists
- The mediating gauge bosons are:  $\gamma, W^\pm, Z$
- This theory only generates massless particles!
- From experiment:

$$m_W = 80.425 \pm 0.038 \text{ GeV}$$

$$m_Z = 91.1876 \pm 0.0021 \text{ GeV}$$

- The problem is resolved via the *Higgs Mechanism* and *spontaneous symmetry breaking*
- The Higgs boson has not been directly confirmed yet



# Strong Interaction

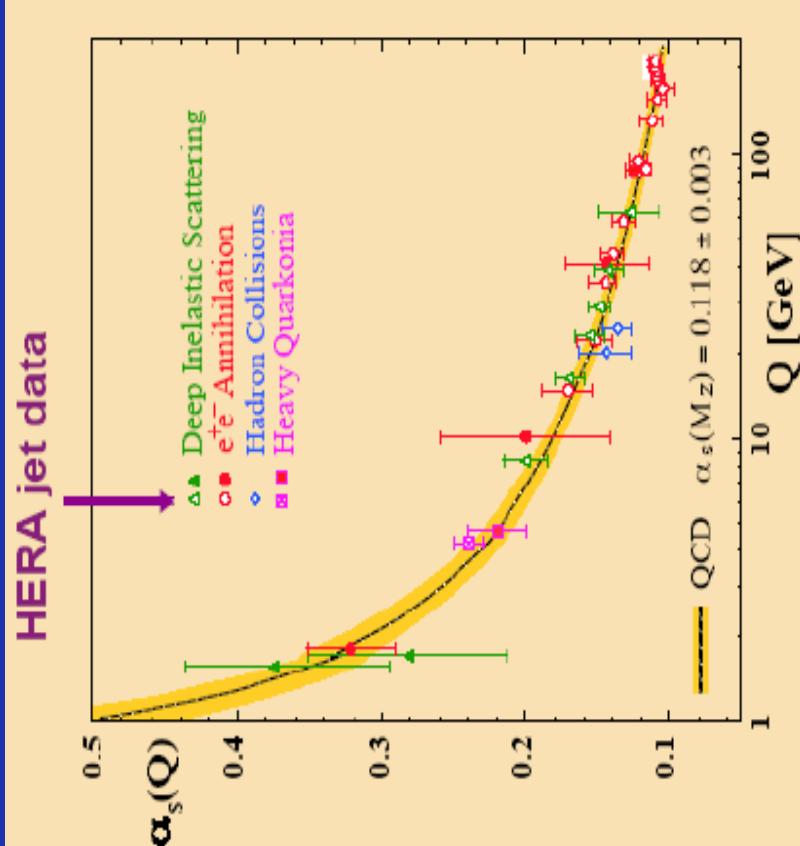
- *Quantum Chromo Dynamics* (QCD) is the QFT describing the strong interaction
- The mediating gauge bosons are called *gluons*
- There are three types of color charges: *red, green, blue* (analogous to electric charge)
- Quarks carry one *color* charge
- Each gluon carries a color and anti-color charge
- Gluons can interact with each other (QCD is non-abelian)
- Partons = Quarks & Gluons
- At large distances parton interactions become large: *confinement*
- At small distances parton interactions become small: *asymptotic freedom*



# The running coupling constant in QCD

$\alpha_s$  varies with the momentum transferred in interactions ( $Q^2$ ):

$$\alpha_s(Q^2) = \frac{12\pi}{(11c - 2n_f)\log(Q^2/\Lambda^2)}$$

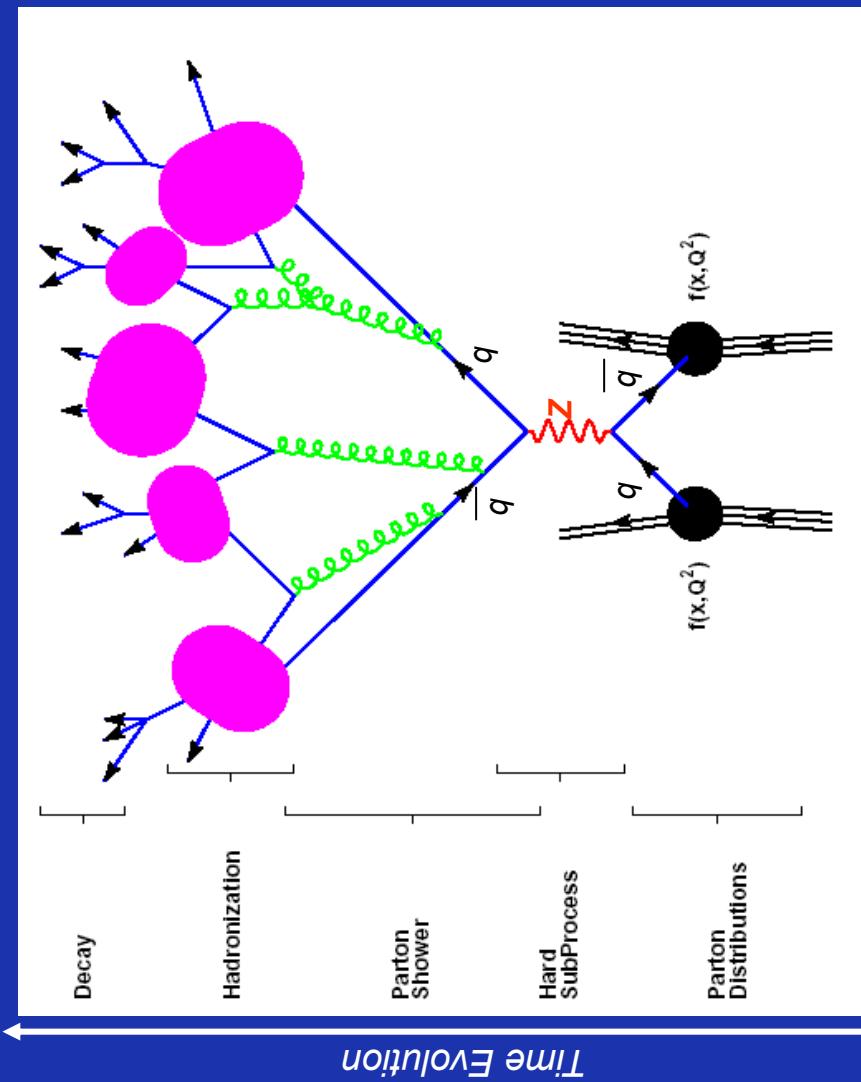


Based on many experiments

# Modeling a $p\bar{p}$ Collision

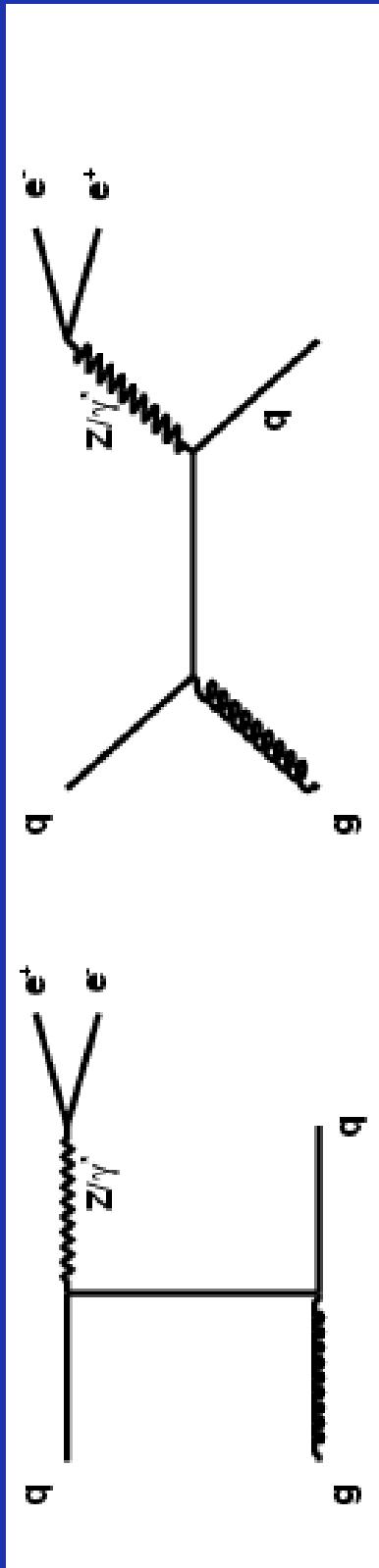


- PDFs describe the momentum distributions of constituent partons
- $\bar{q}q \rightarrow Z \rightarrow q\bar{q}$  describes the hard subprocess
- Parton branching results in parton shower
- Hadronization due to creation of color-neutral hadrons
- Hadrons decay



# Why study $Z/\gamma^*$ ( $\rightarrow e^+e^-$ ) + Jets ? (1)

- $Z/\gamma^*$  decay provides a distinctive event signature: 2 high  $p_T$  electrons



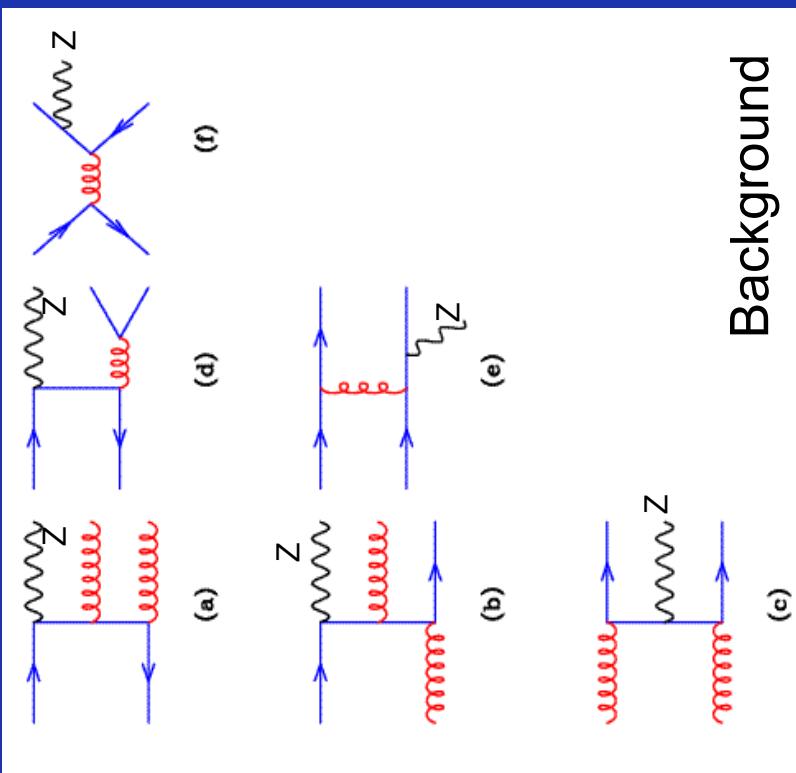
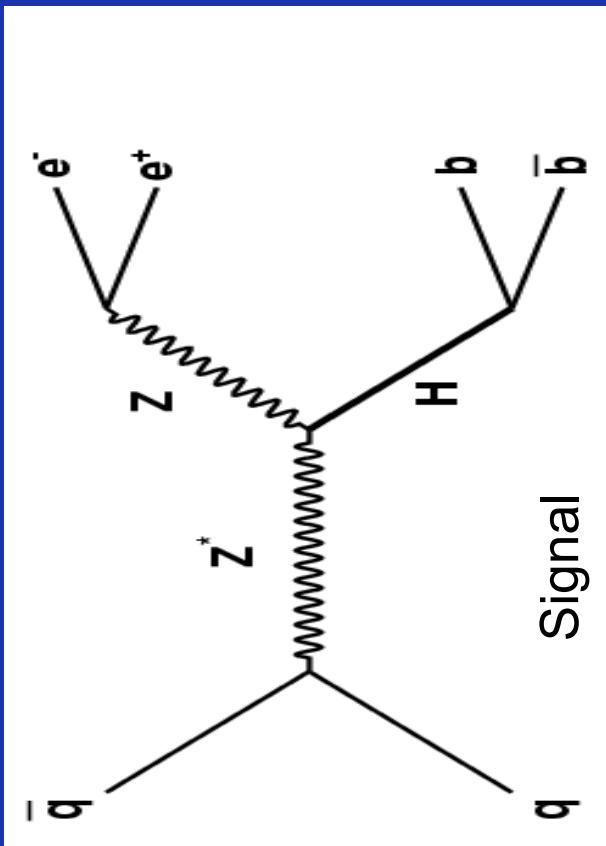
*LO Z+1 parton diagrams*

- Test perturbative QCD predictions by comparing data results to event simulations (MC) that combine n-parton matrix element calculations with simulations for parton showering and hadronization

# Why study $Z/\gamma^*$ ( $\rightarrow e^+e^-$ ) + Jets ? (2)



- Background to Higgs searches:



- Improve on previous measurements: CDF Run I result with  $100 \text{ pb}^{-1}$ ,  $\sqrt{s} = 1.8 \text{ TeV}$ , and covering up to 4 jets (PRL 77:448, 1996)

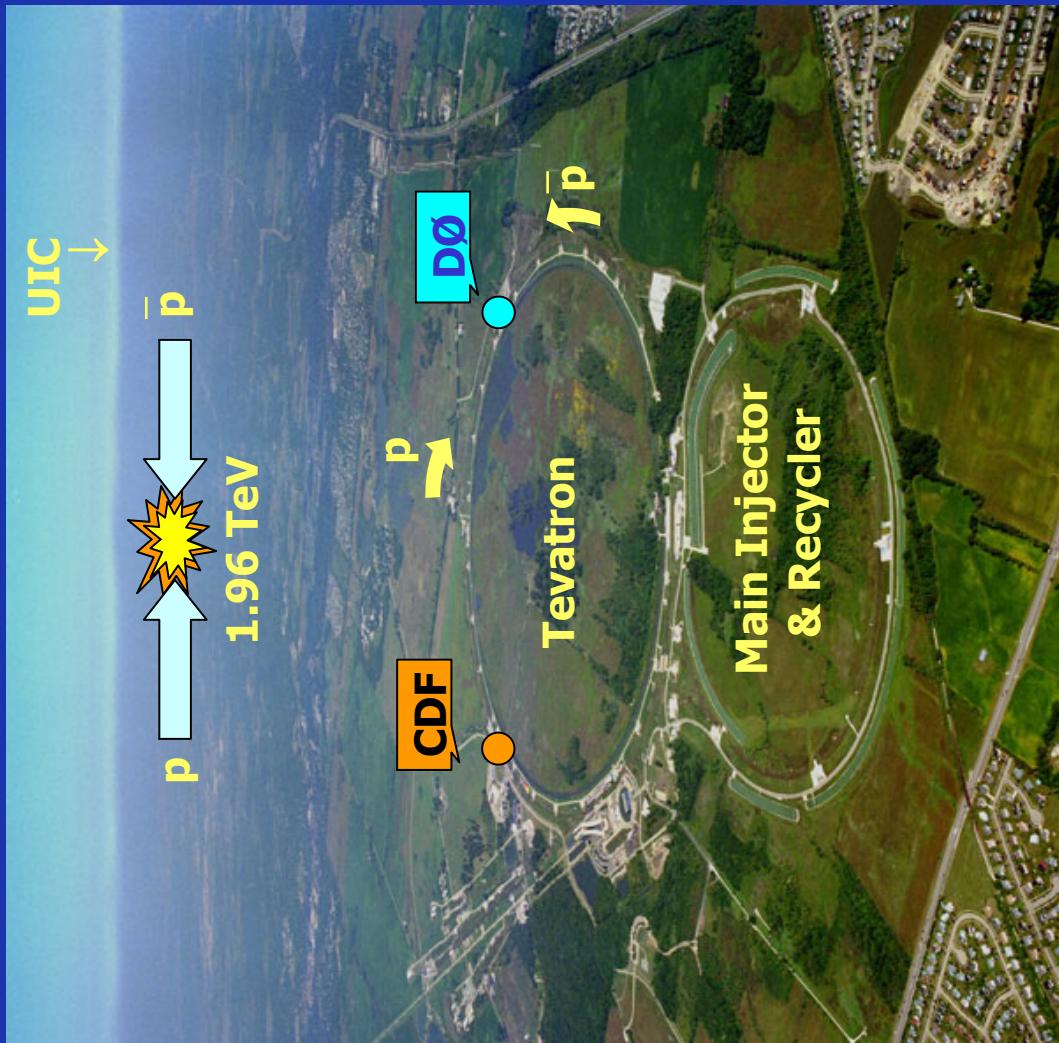


# Experimental Apparatus

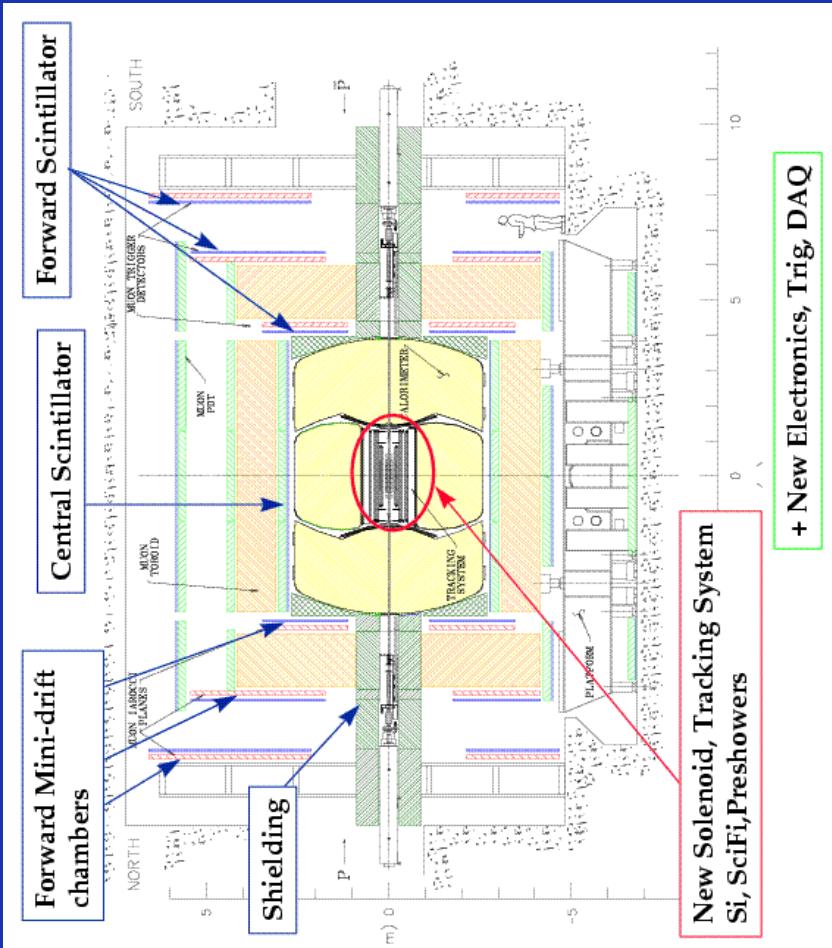
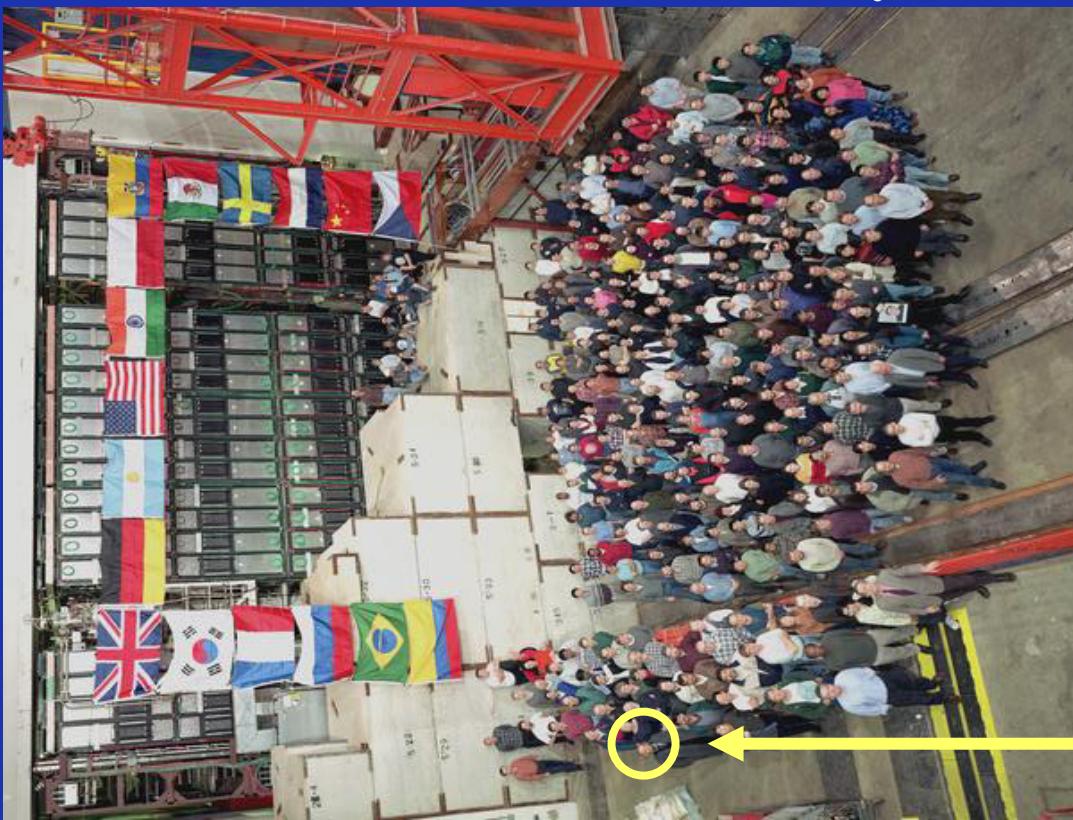
# Fermilab Accelerators



- Colliding protons and antiprotons at  $\sqrt{s} = 1.96$  TeV
- $36 \times 36$  proton and antiproton bunches collide at 1.7 MHz
- Run IIa:
  - 2002-2005
  - $>1 \text{ fb}^{-1}$
- Run IIb:
  - 2006-2009
  - $\sim 6-8 \text{ fb}^{-1}$
- This analysis was performed with the D $\bar{Q}$  detector



# D $\emptyset$ Detector

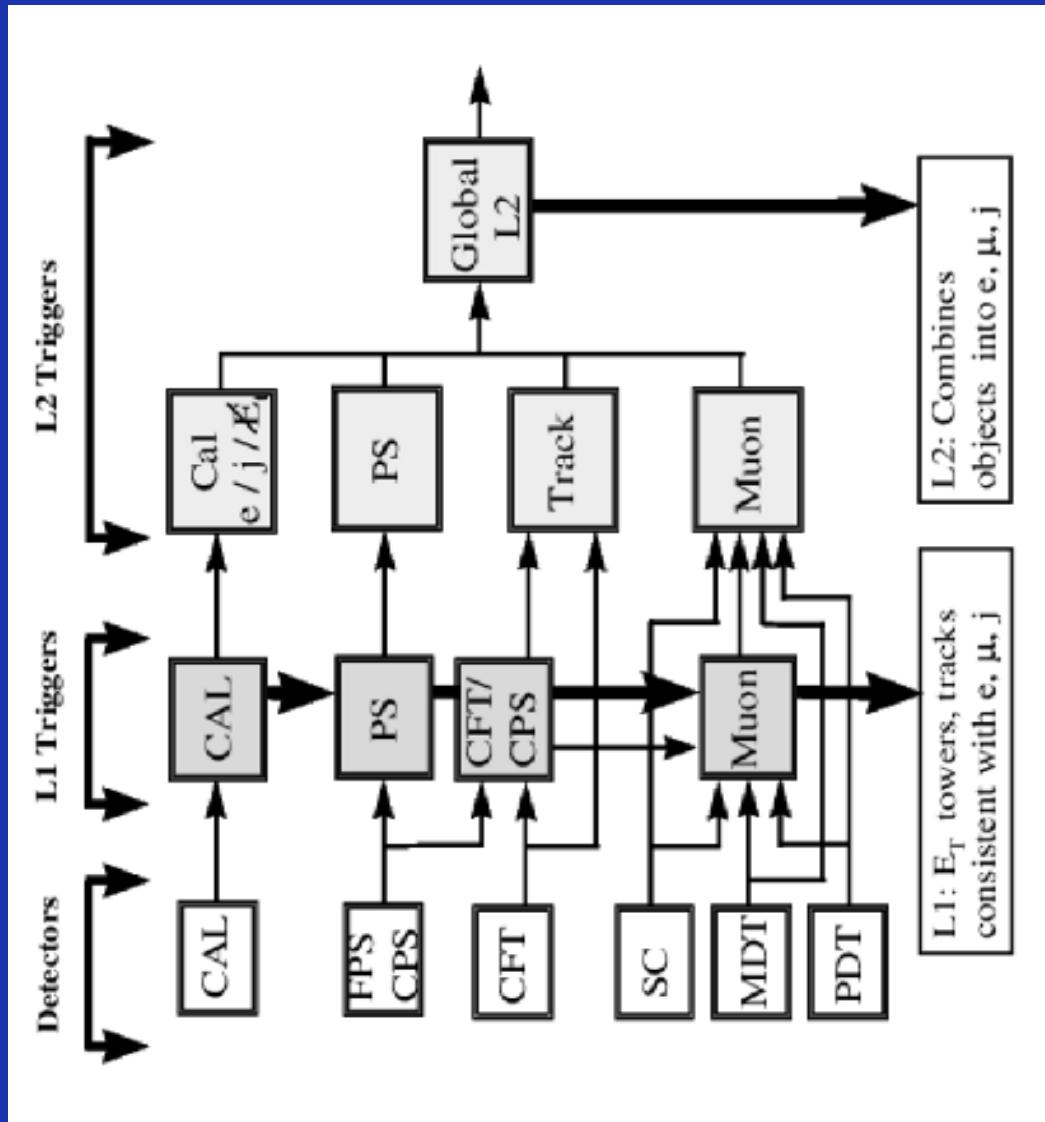


- Subdetectors important to this analysis:
  - Central Tracking System: Silicon and Fiber Trackers in 2 T magnetic field
  - Liquid Argon/Uranium Calorimeter

# Trigger and DAQ Systems



- Trigger system consists of three trigger levels:  
 $L_1, L_2, L_3$
- Event rate reduction from 1.7 MHz to 50 Hz ( $\approx 200$  kBytes/event)
- $L_1$  uses fast hardware (FPGAs)
- $L_2$  uses hardware engines associated with specific detector subsystems and a single global processor for the final  $L_2$  trigger decision
- $L_3$  consists of a PC farm
- Events that pass all three levels of triggering are stored for further offline reconstruction and analysis

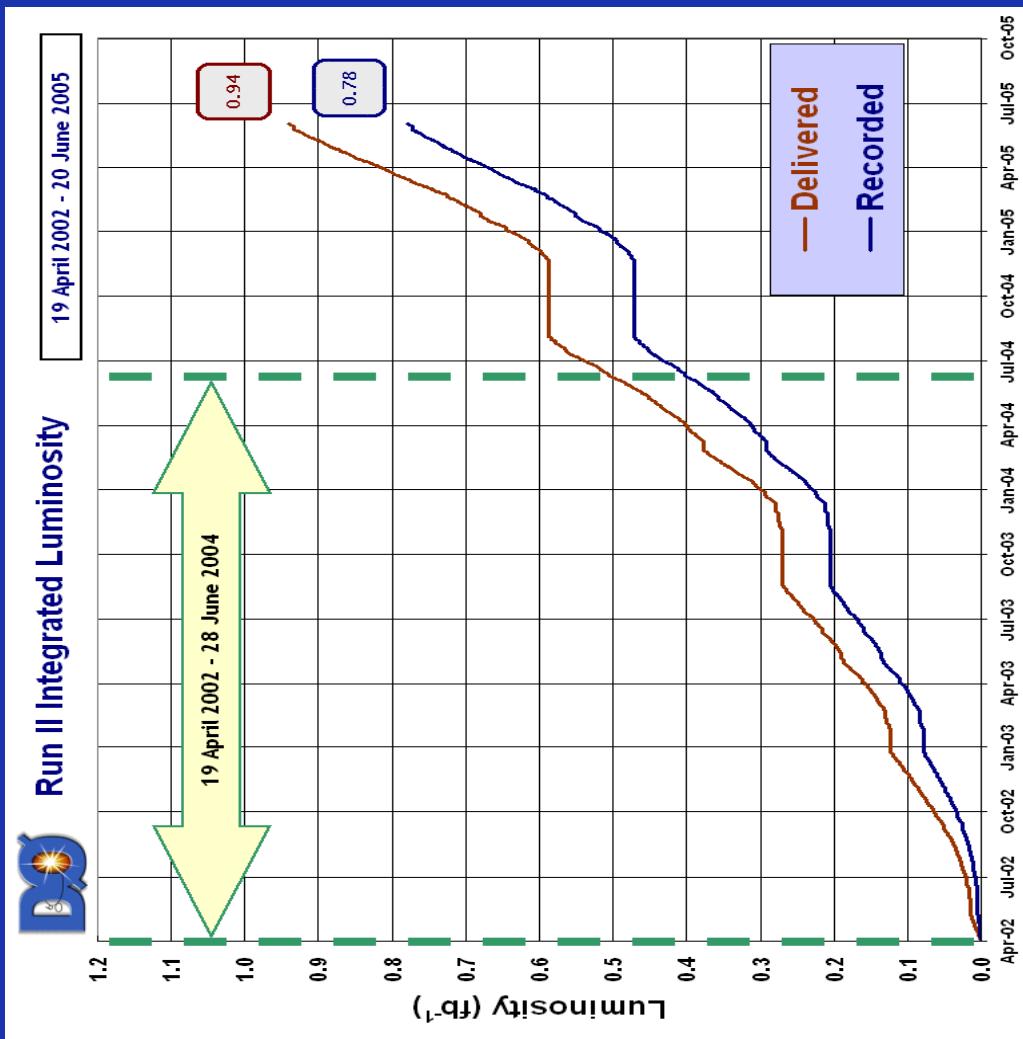


# Data and MC Samples



# Data Sample

- Based on data recorded between April 2002 and June 2004 ( $\approx 876$  million events)
- Events are selected (triggered) based on the presence of at least one EM Object
- Additional data quality requirements are applied
- Total integrated luminosity for this analysis =  $343 \text{ pb}^{-1}$



# MC Samples

- PYTHIA:
  - Simulates  $q\bar{q} \rightarrow Z/\gamma^* \rightarrow e^+e^-$  LO hard process
  - ISR/FSR parton showering provides QCD corrections to LO
- ALPGEN + PYTHIA:
  - Calculates tree level matrix elements for  $Z/\gamma^* + 1, 2, 3$  jets
  - Combined with PYTHIA to simulate parton showering and hadronization
- MADGRAPH + PYTHIA (“CKKW “samples”):
  - Calculates tree level matrix elements for  $Z/\gamma^* + 1, 2, 3$  jets
  - Combined with PYTHIA to simulate parton showering and hadronization
- Follows the CKKW prescription to avoid double counting when combining different multiplicity final states
- MC@NLO:
  - Calculates cross sections for  $Z/\gamma^* (\rightarrow e^+e^-)$  at NLO for up to 2 partons in the final state



# Event Selection: Electrons and Zs

- Trigger:
  - Requiring  $\geq 1$  EM object per event
  - Example: L1 10 GeV  $\rightarrow$  L2 12 GeV  $\rightarrow$  L3 20 GeV
- Primary Vertex cut:  $|PVZ| < 60$  cm
- Select 2 Electrons:
  - High  $p_T$  electrons:  $p_T > 25$  GeV
  - Only use “central” electrons:  $|\eta| < 1.1$
  - High electromagnetic fraction:  $EMF > 0.9$
  - Isolated:  $I_{\text{so}} < 0.15$
  - Shower shape cut:  $HMx(7) < 12.0$
  - At least one track match
  - At least one electron must have fired the trigger
- Z Selection:
  - $75 \text{ GeV} < M_{ee} < 105 \text{ GeV}$



# Event Selection: Jets

- Jet reconstruction is based on *Run II Midpoint Cone Algorithm* ( $R_{cone} = 0.5$ )
- $p_T > 20 \text{ GeV}$
- $|\eta| < 2.5$
- Removing jets overlapping with electrons from  $Z/\gamma^*$  within  $\Delta R = 0.4$
- Additional quality cuts:
  - $0.05 < \text{EMF} < 0.95$
  - $\text{HotF} < 10$
  - $\text{N90} > 1$ .
  - $\text{CHF} < 0.4$
  - L1 confirmation

Sample	N	Fraction
$Z/\gamma^* + 0 \text{ jets}$	12,247	0.8815
$Z/\gamma^* + 1 \text{ jets}$	1,427	0.1027
$Z/\gamma^* + 2 \text{ jets}$	189	0.0136
$Z/\gamma^* + 3 \text{ jets}$	25	0.0018
$Z/\gamma^* + 4 \text{ jets}$	3	0.0002
$Z/\gamma^* + 5 \text{ jets}$	2	0.0001
Total	13,893	1.0000

*Exclusive Jet Multiplicities*

$$(\Delta R = \sqrt{\Delta \eta^2 + \Delta \Phi^2})$$





# The $Z/\gamma^*$ ( $\rightarrow e^+e^-$ ) + $\geq n$ Jet Cross Sections

# General Strategy

Inclusive  $Z/\gamma^*$  ( $\rightarrow e^+e^-$ ) Cross Section :

$$\sigma \times BR(Z / \gamma^* \rightarrow e^+e^-) = \frac{N - B}{L \times A \times \varepsilon_{tot}}$$

- N = total number of events in  $75 \text{ GeV} < M_{ee} < 105 \text{ GeV}$
- B = total number of background events in  $75 \text{ GeV} < M_{ee} < 105 \text{ GeV}$
- L = Luminosity ( $343 \text{ pb}^{-1}$ )
- A = Acceptance
- $\varepsilon_{tot}$  = total efficiency to identify  $e^+e^-$  pairs from  $Z/\gamma^*$  decays  
(Trigger, Electron, Track Matching)

$Z/\gamma^*$  ( $\rightarrow e^+e^-$ ) +  $\geq n$  jet cross sections:

- Examine variation of  $\varepsilon_{tot}$  w.r.t. jet multiplicity
- Jet reconstruction and identification (Jet reco/ID)
- Unsmeearing
- Electron-jet-overlap



# The “tag-and-probe” method

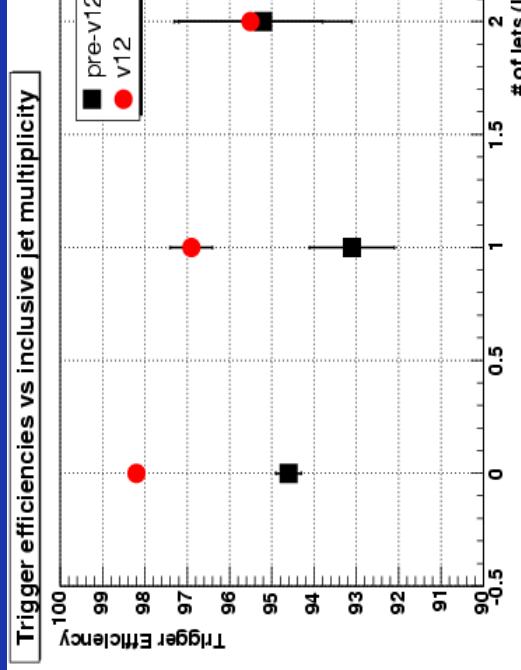
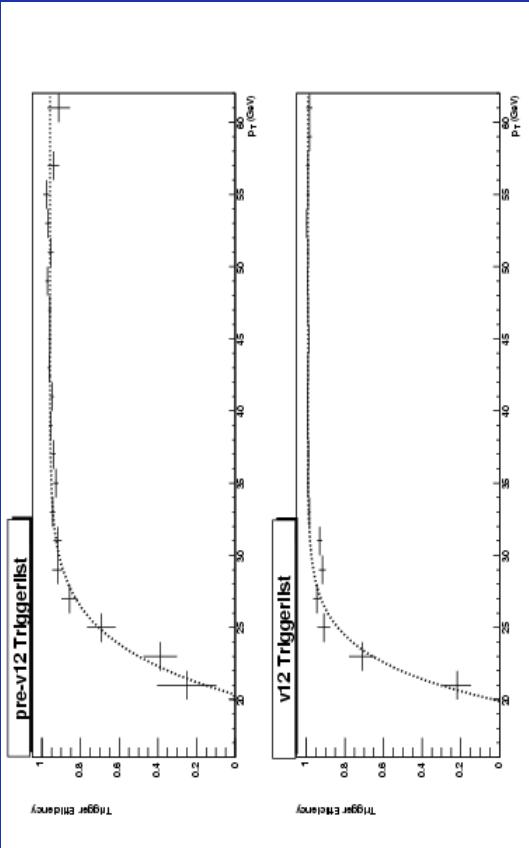
- A tool to derive efficiencies (trigger, electrons):
  - Step 1: Select a “good” tag electron (EM calorimeter object matched with a track)
  - Step 2: Select a probe object (track matched EM object for trigger efficiencies, track for electron efficiencies)
  - Step 3: make sure that both tag and probe objects are associated with a  $Z/\gamma^*$  decay (imposing a  $M_{ee}$  cut)
  - Step 4: Use the probe object to query for an electron passing trigger requirements (trigger efficiency), or the presence of a reconstructed electron passing quality cuts (electron efficiencies)
- Efficiencies can be parameterized w.r.t. probe object quantities ( $p_T, \Phi$ )



# Trigger Efficiency

*The efficiency for an electron to pass all trigger levels.*

- Need to split the data sample into two pieces since triggers changed
- Method: “tag-and-probe” method, where a probe electron is tested to pass trigger conditions
- Applying trigger efficiency vs electron  $p_T$  as correction to  $Z/\gamma^* \rightarrow e^+e^- + X$  sample



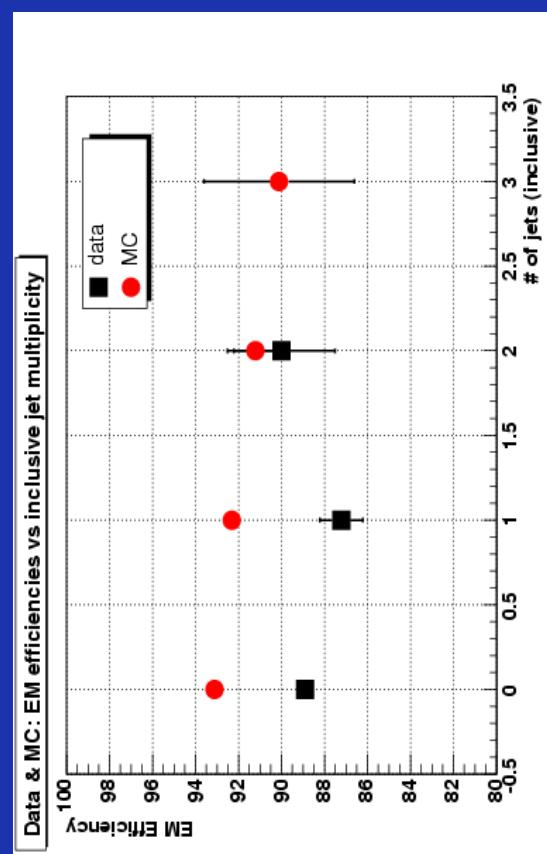
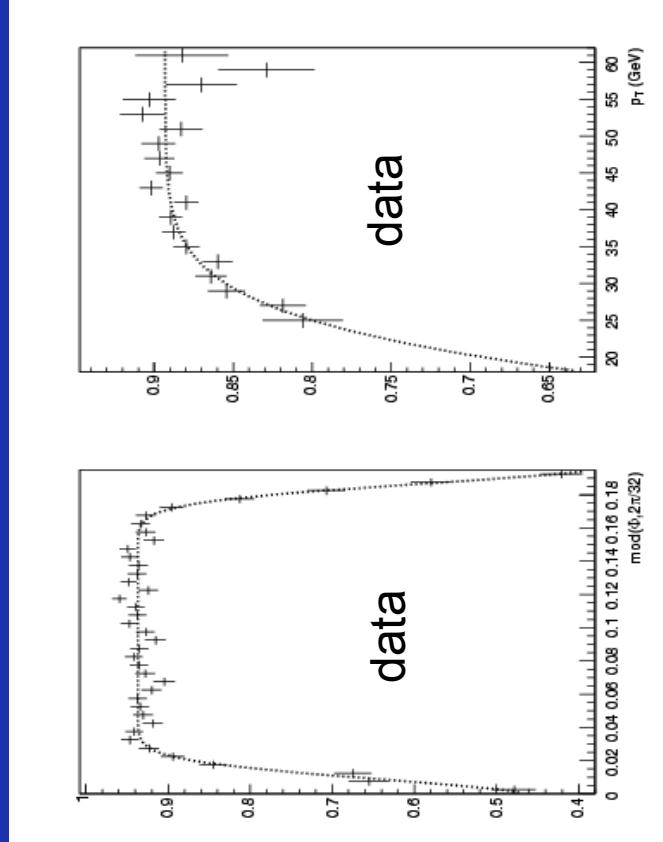
- Applying trigger efficiency vs electron  $p_T$  as correction to all jet multiplicity samples
- Fluctuations of trigger efficiencies w.r.t. jet multiplicity are taken into account as systematic uncertainties

# EM Reco/ID Efficiency



The efficiency to reconstruct an electron candidate which passes all quality cuts.

- Method: tag-and-probe, where a probe track is tested for the presence of an electron
- Applying EM efficiency vs  $\Phi$  and  $p_T$  as correction to  $Z/\gamma^* \rightarrow e^+e^- + X$  sample



- No big variations in EM efficiency vs jet multiplicity are observed in data
- Applying EM efficiency vs  $\Phi$  and  $p_T$  as correction to **all** jet multiplicity samples in data

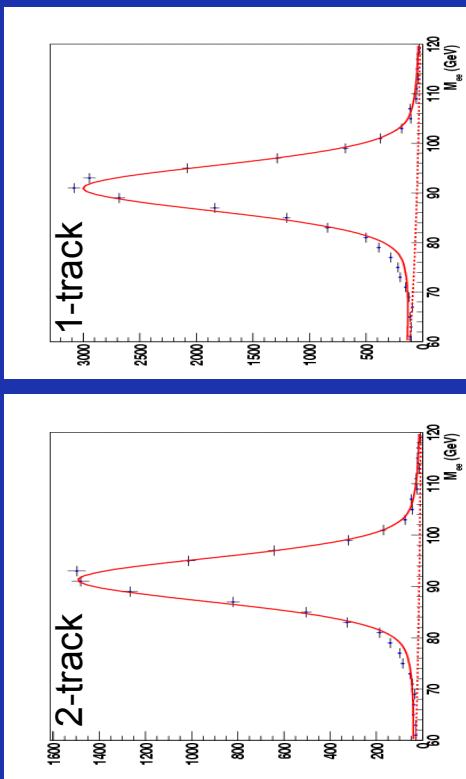


# EM-Track Match Efficiency

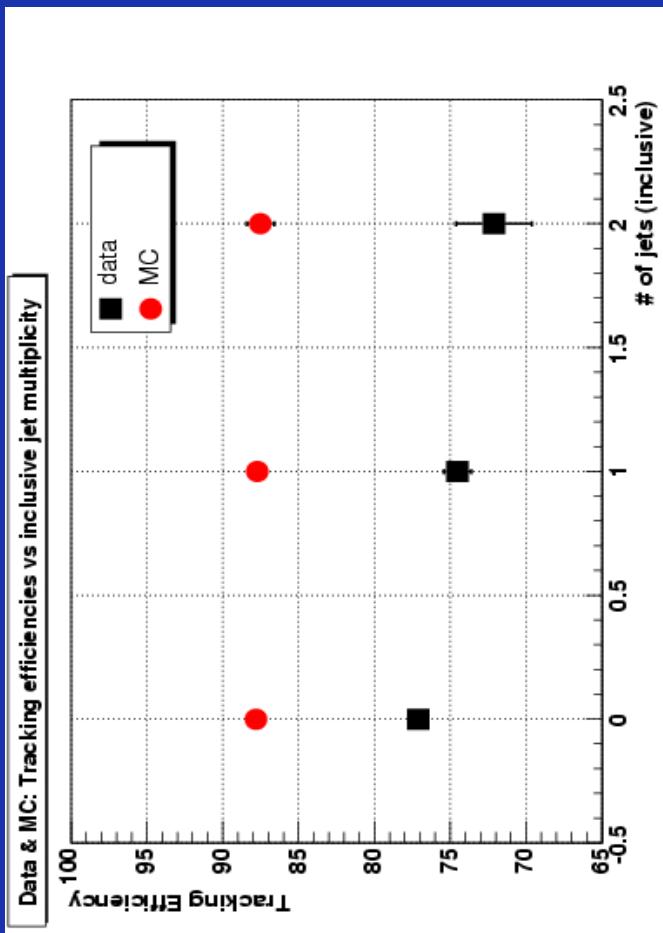
The efficiency to find at least one electron candidate that has a matched track.

- Method: ratio of 1-track and 2-track diem invariant mass histograms yields the efficiency:

$$\varepsilon_{\text{track}} \sim (\# \text{ of 2-trk evts}) / (\# \text{ of 1-trk evts})$$



- Applying 0-jet, 1-jet, and 2-jet values to the respective jet multiplicity samples, and using 2-jet values for 3-jet, 4-jet, and 5-jet samples



# Acceptance

*The efficiency for fiducial and kinematic cuts.*

- Correct for:
  - Primary vertex cut
  - Electron  $p_T$  and  $\eta$  cuts
  - $M_{ee}$  cut
- Can only be derived from MC
- Higher jet multiplicity means “harder” Z  $\Rightarrow$  higher acceptance

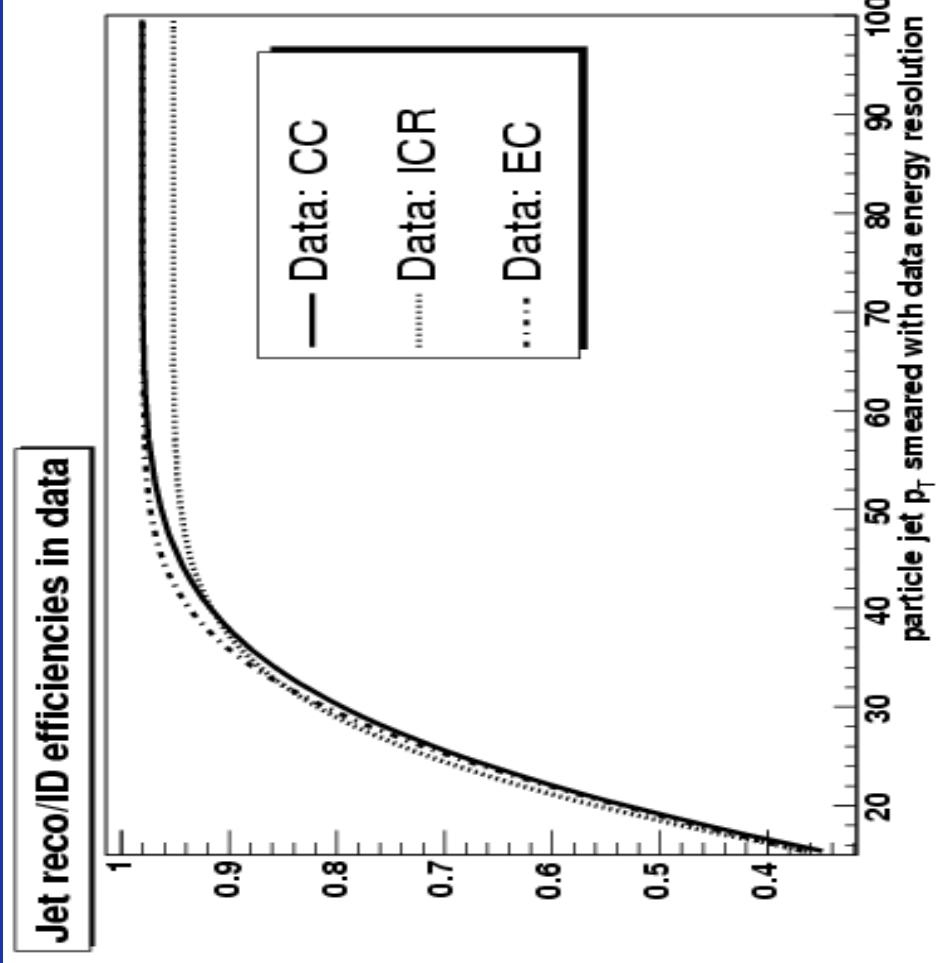
Jet Multiplicity	Acceptance
$\geq 0$	$21.4 \pm 0.1\%$
$\geq 1$	$25.1 \pm 0.2\%$
$\geq 2$	$25.4 \pm 0.2\%$
$\geq 3$	$27.4 \pm 0.3\%$
$\geq 4$	$28.5 \pm 0.7\%$
$\geq 5$	$30.3 \pm 1.9\%$



# Jet Reco/ID Efficiency

The efficiency to find a jet which passes all quality cuts.

- A scaling factor is derived following the “Z  $p_T$  Method”.
  - Select events with Z candidates
  - Probe for a recoiling jet opposite in  $\Phi$
  - Measure the “efficiency” of finding a recoiling jet as a function of Z  $p_T$  in data and MC
  - Derive a scaling factor by taking the ratio of Z  $p_T$  efficiency in data and MC
  - Apply the scaling factor to MC to get “tuned MC”
  - Use the tuned MC to derive “straight efficiency”.
    - Matching particle level jets with calorimeter level jets within  $\Delta R=0.4$
  - Parameterize efficiency versus smeared particle jet  $p_T$



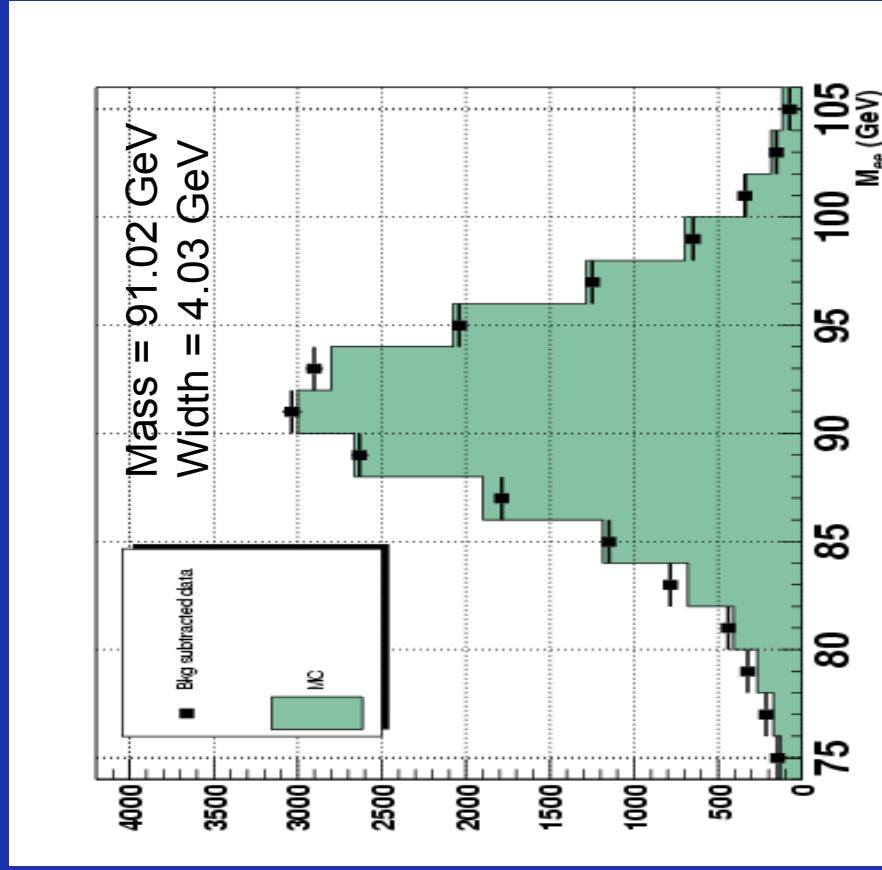
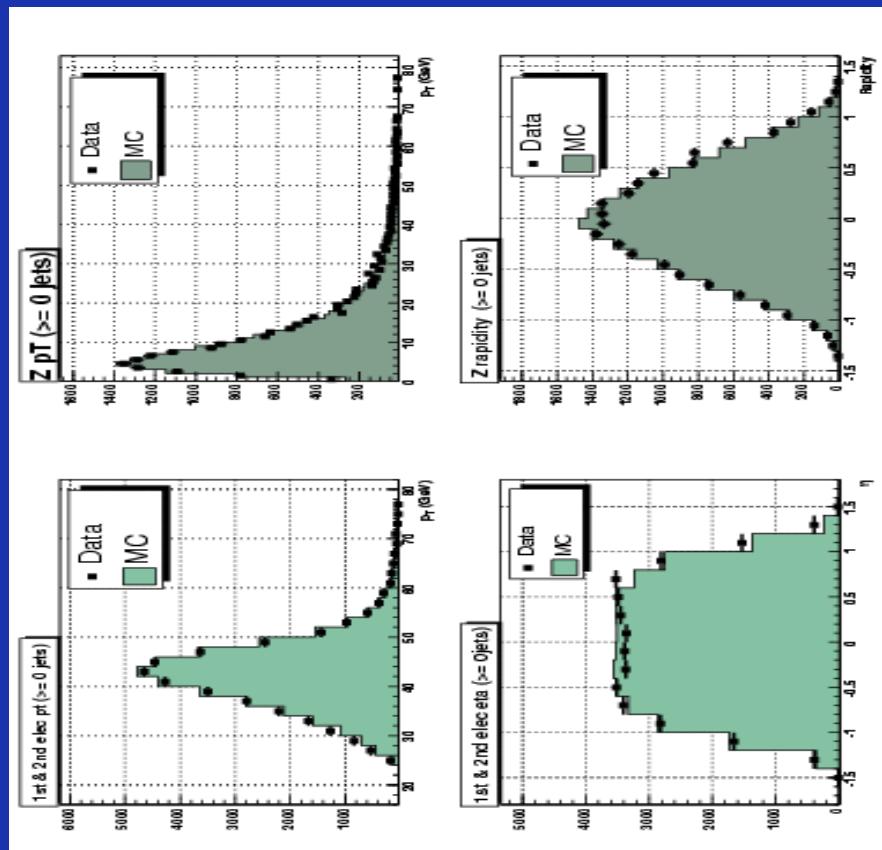
# Data vs MC



- Applying all corrections
  - EM
  - Trigger
  - Tracking
  - Jet reco/ID scaling
- MC distributions are normalized to the number of events in data

# $Z/\gamma^* (\rightarrow e^+e^-) + X$ : Electrons and Zs

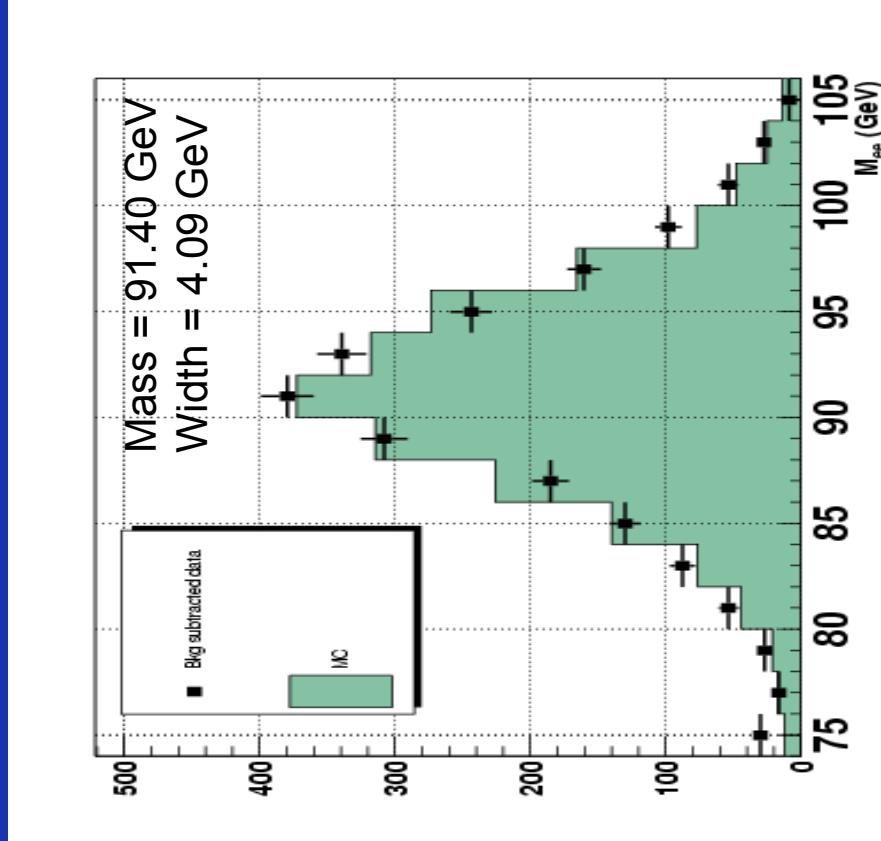
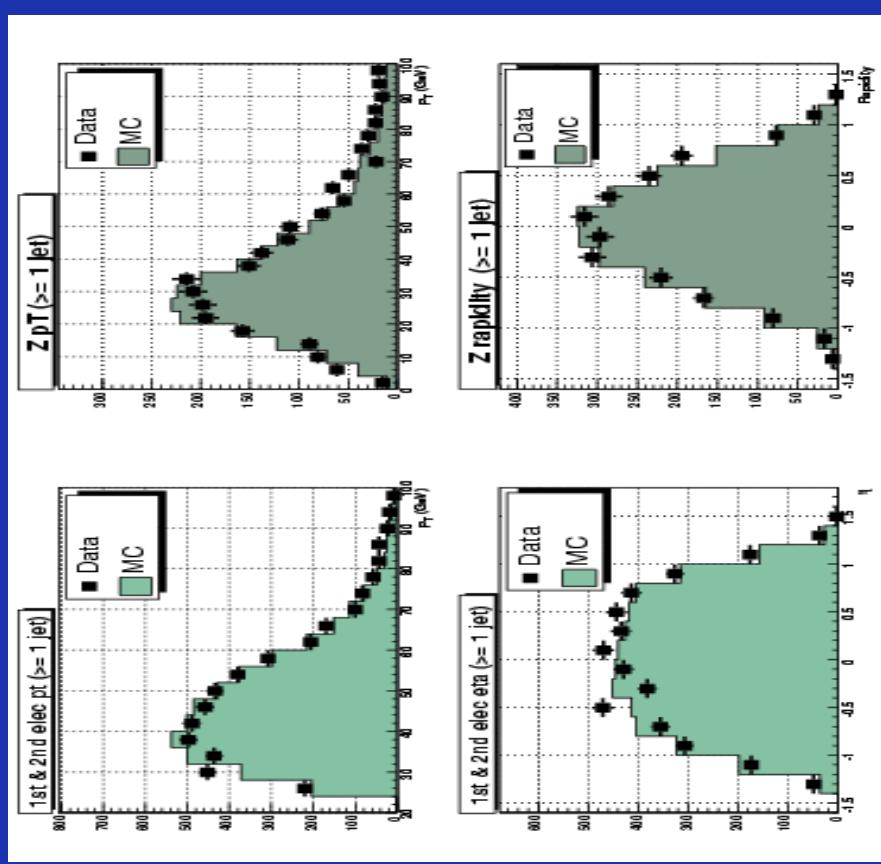
Data sample contains  $\approx 14k$  events - PYTHIA MC





# Z/ $\gamma^*$ ( $\rightarrow e^+e^-$ ) + $\geq 1$ Jet: Electrons and Zs

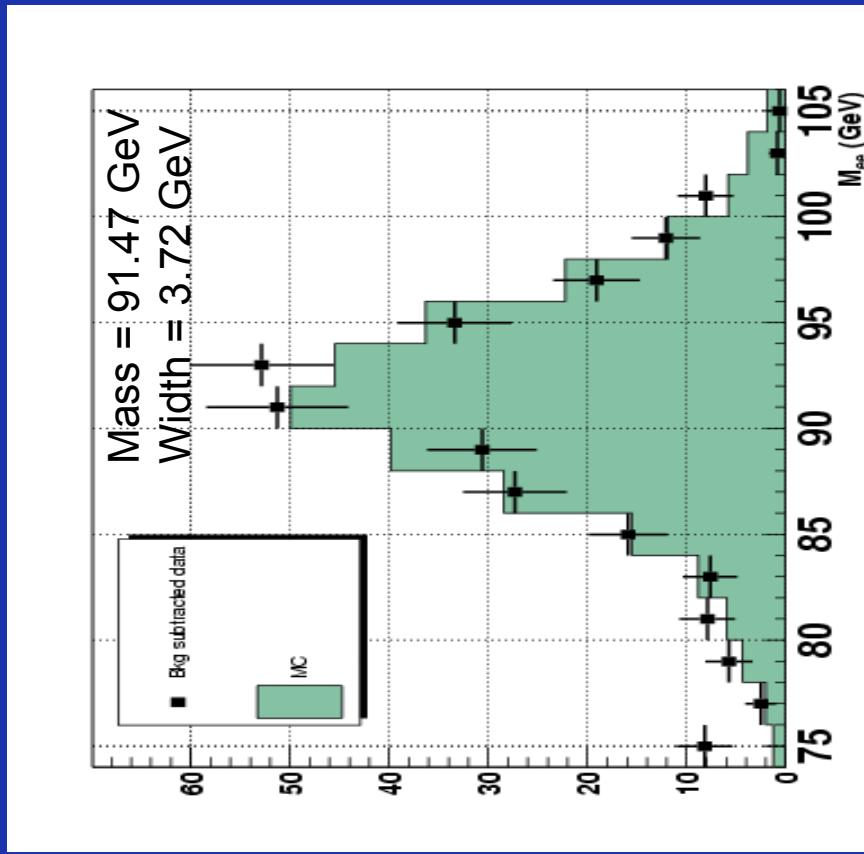
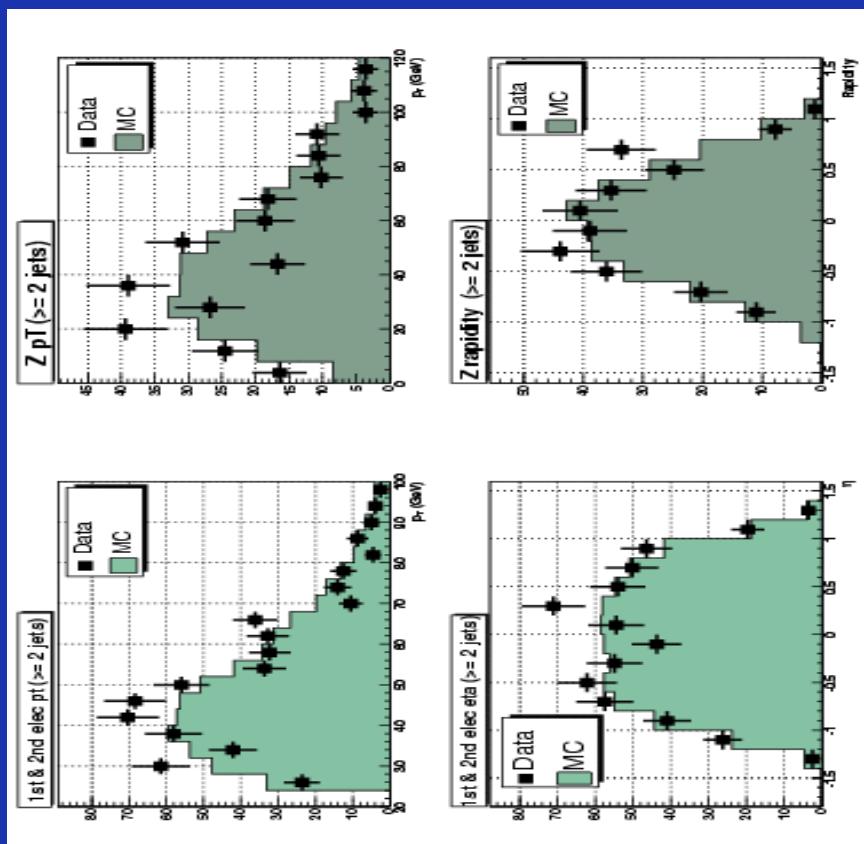
Data sample contains  $\approx 1.6k$  events - ALPGEN+PYTHIA MC



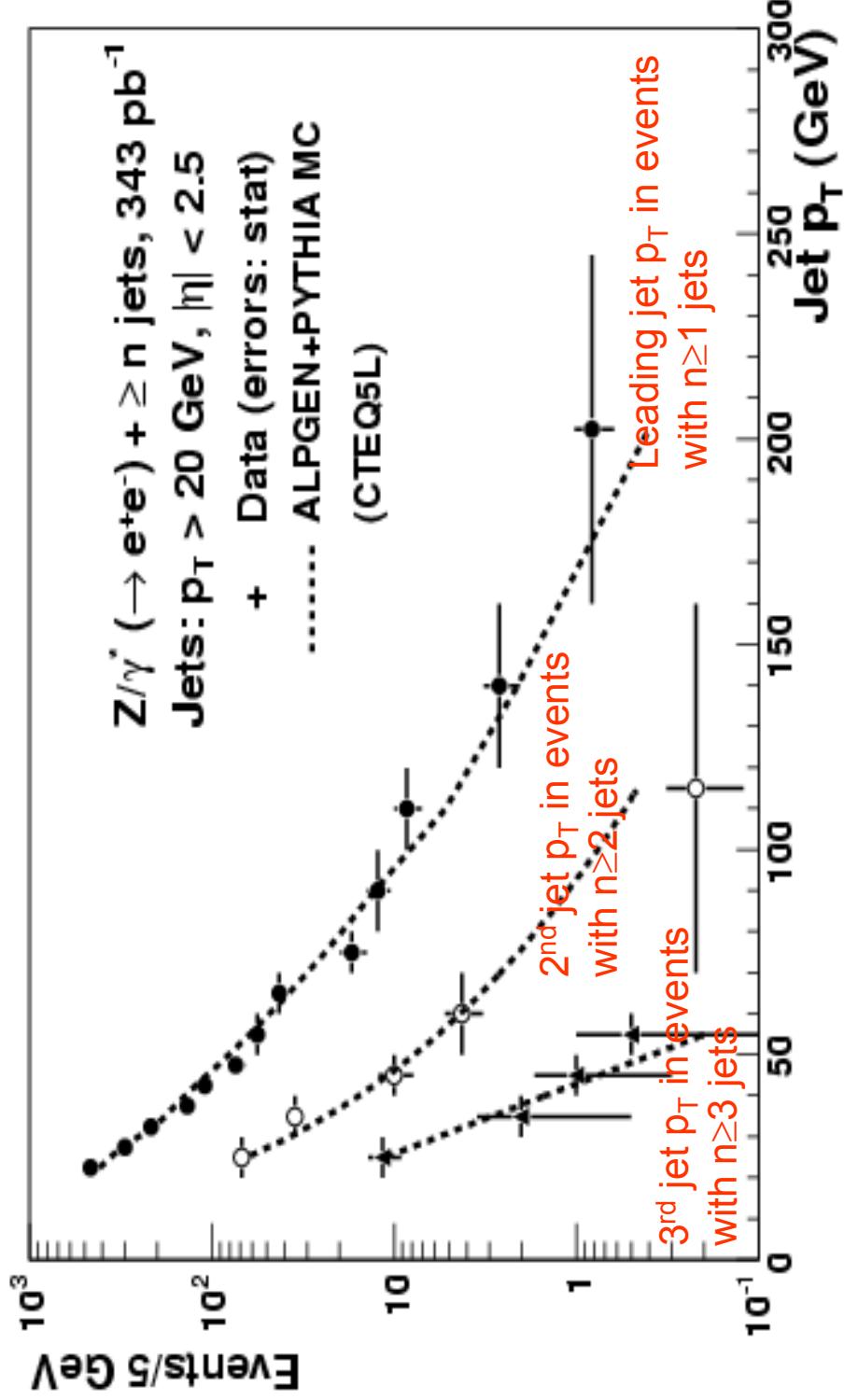


# $Z/\gamma^*$ ( $\rightarrow e^+e^-$ ) + $\geq 2$ Jets: Electrons and $Zs$

Data sample contains  $\approx 200$  events - ALPGEN+PYTHIA MC



# Jet $p_T$ spectra

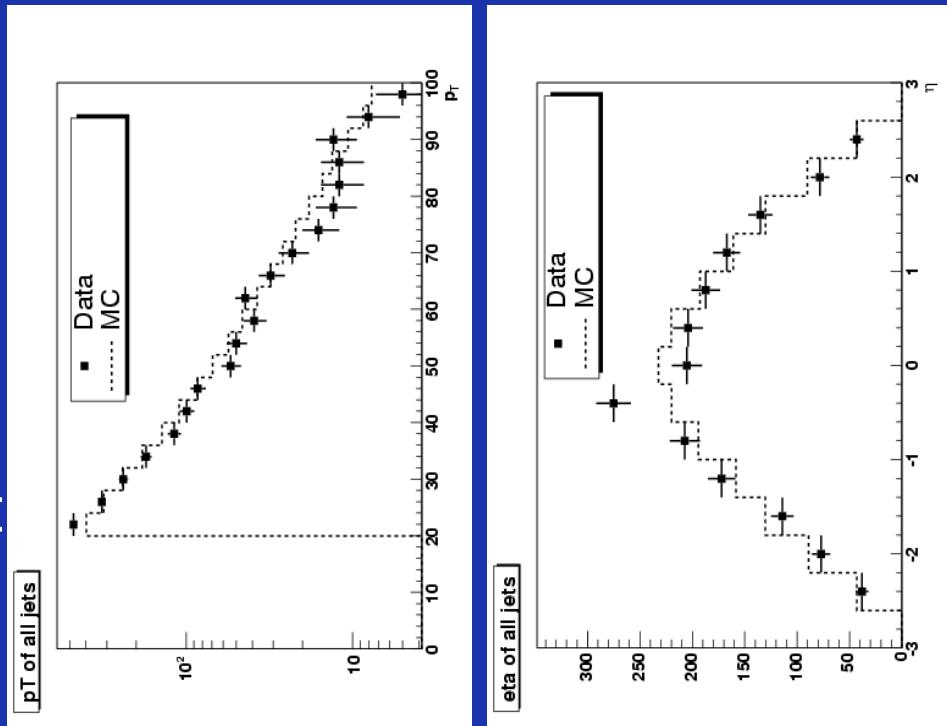


Data to theory (ALPGEN+PYTHIA) comparison for jet  $p_T$ 's

# Unsmearing and Jet Reco/IID Correction (1)



To determine particle level cross sections, we correct the measured data jet multiplicities for event migration due to the finite jet energy resolution of the detector. Jet reco/IID efficiencies are also applied.

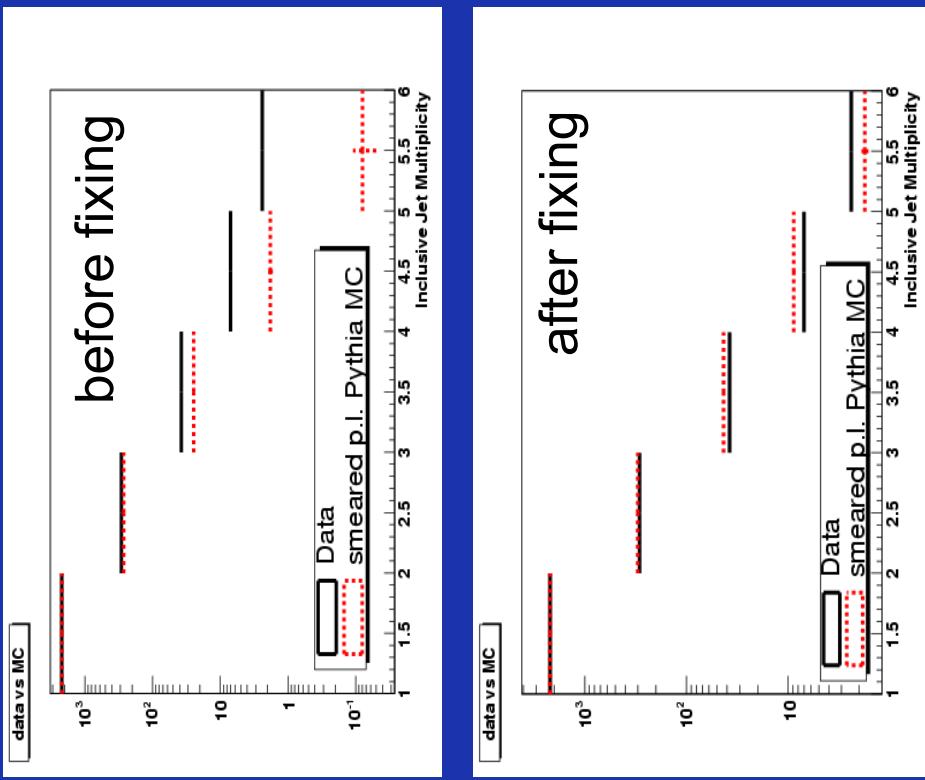


- Using particle level PYTHIA sample with  $2 \rightarrow 2$  subprocesses\*
- No detector simulation
- $p_T$  values of particle jets are smeared with data jet energy resolution

$$\begin{aligned} * & f_i \bar{f}_i \rightarrow g Z \\ & f_i g \rightarrow f_i Z \end{aligned}$$

# Unsmearing and Jet Reco/ID Correction (2)

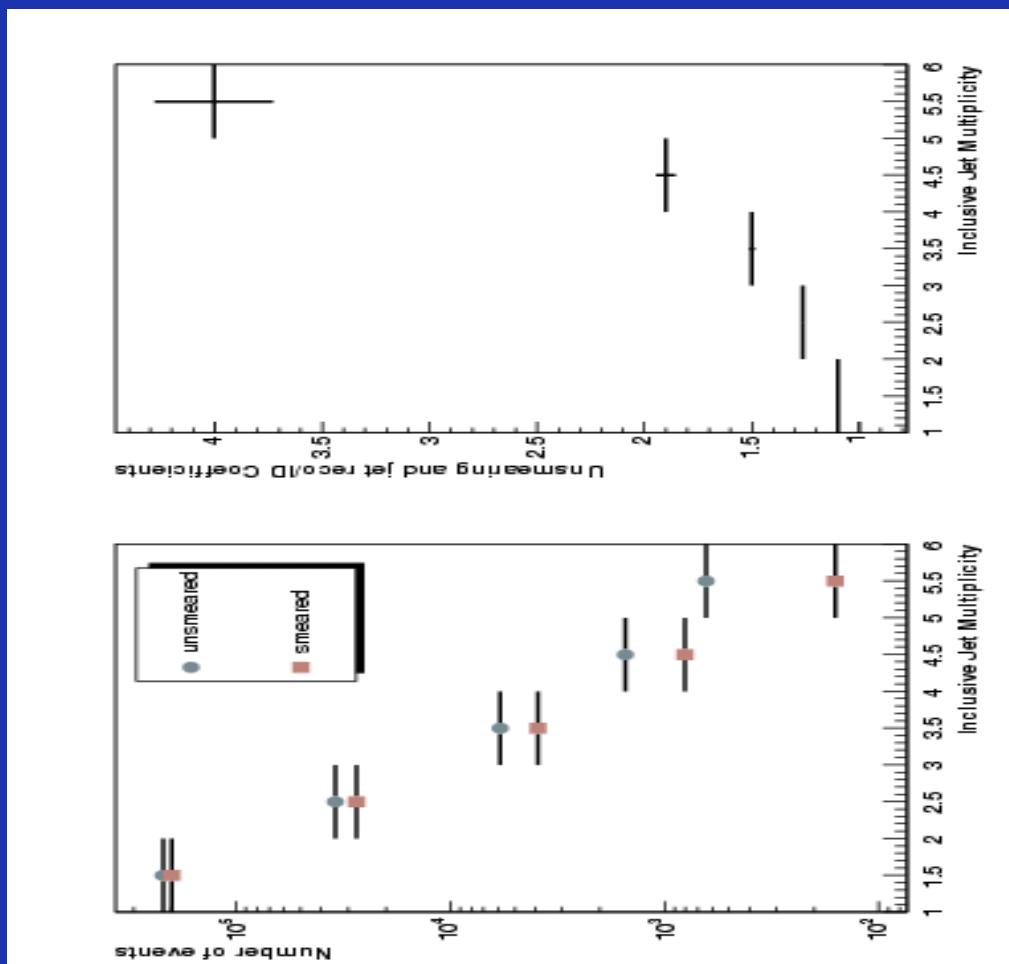
- Comparing inclusive jet multiplicities between PYTHIA and data
- Disagreement due to PYTHIA lacking higher order contributions at the hard scatter level
- Corrected by taking ratio between data and MC jet multiplicities and applying corrective weights to MC
- Fixed PYTHIA agrees better



# Unsmearing and Jet Reco/ID Correction (3)



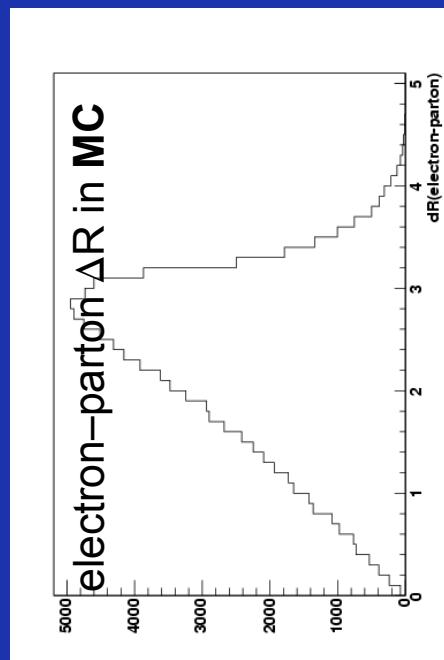
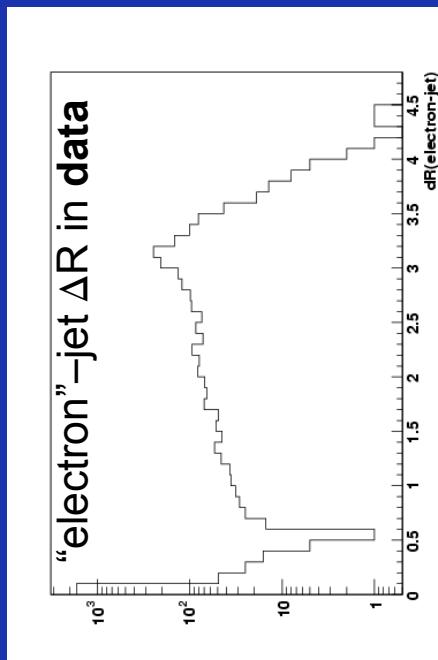
- Using the fixed PYTHIA sample to derive unsmearing and jet reco/ID coefficients
- Taking the jet multiplicity ratios with and w/o applying jet  $p_T$  smearing (and applying jet reco/ID efficiencies)
- Applying the ratios as multiplicative factors to the measured jet multiplicities in data



# Electron-jet-Overlap Correction

*The electron-jet-overlap correction provides an adjustment for the fraction of jets that are rejected due to an overlap with electrons from  $Z/\gamma^*$  decays.*

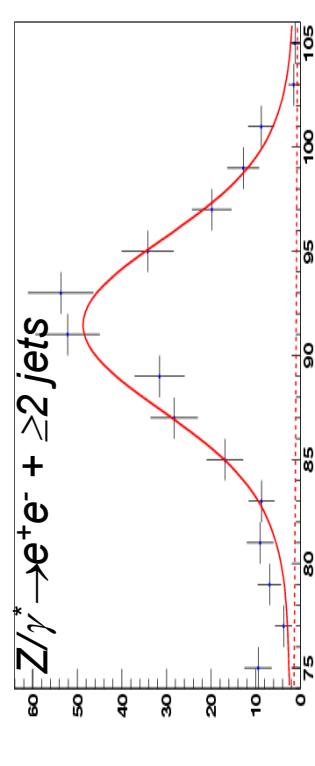
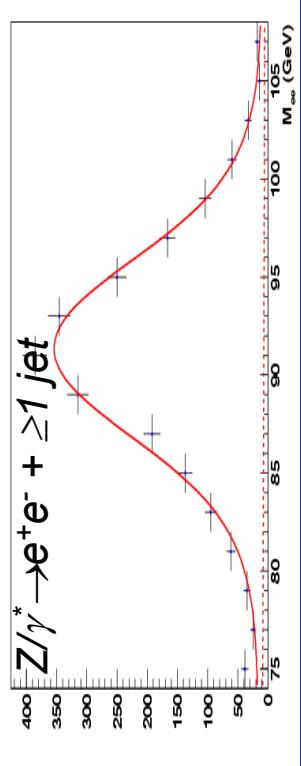
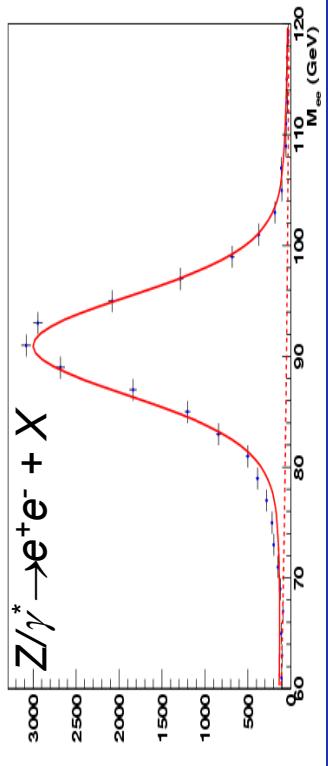
- “Fake” jets that pass quality cuts are generated by electron energy deposits
  - All jets within  $\Delta R=0.4$  of electrons from  $Z/\gamma^*$  decays are rejected
  - Use PYTHIA MC to correct for the fraction of real jets that gets rejected
  - Taking the jet multiplicity ratios with and w/o applying the  $\Delta R$  cut
- | Jet Multiplicity | Electron-Jet-Overlap Coefficients |
|------------------|-----------------------------------|
| $\geq 1$         | 1.059                             |
| $\geq 2$         | 1.075                             |
| $\geq 3$         | 1.092                             |
| $\geq 4$         | 1.109                             |
| $\geq 5$         | 1.125                             |



# Number of signal events (1)

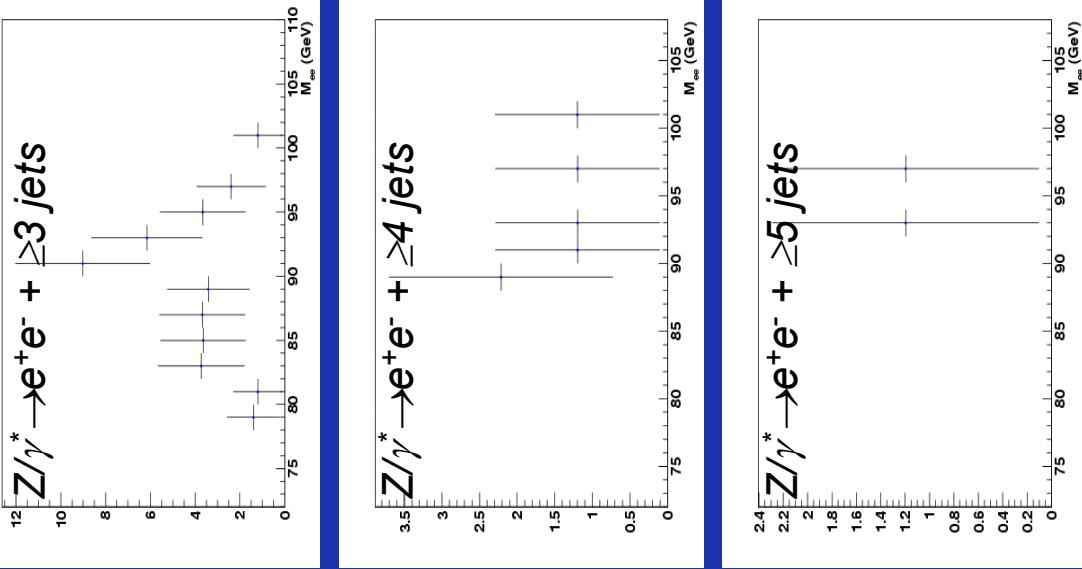
Determining the number of  $Z/\gamma^*$  decay candidates for different jet multiplicity samples after subtracting background.

- Based on corrected dijet invariant mass distributions
- $Z = \text{Breit-Wigner} + \text{Gaussian fit}$
- QCD and  $DY(\gamma^*) = \text{exponential fit}$
- Disentangle QCD from DY by using the known (from MC) fraction of DY events in  $Z/\gamma^* \rightarrow e^+e^-$ : 2.1%



# Number of signal events (2)

- Sideband background subtraction method used for  $\geq 3$  jet sample
- Extrapolating an exponential fit to the number of background events for  $\geq 4$  and  $\geq 5$  jet samples



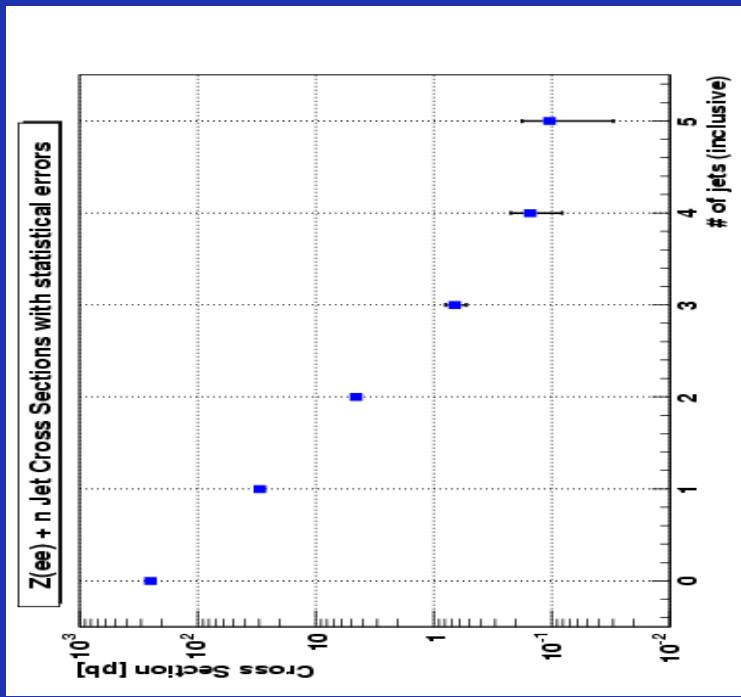
Jet Multiplicity	Signal	Background
$\geq 1$	2550.7	74.6
$\geq 2$	392.0	12.5
$\geq 3$	61.6	3.1
$\geq 4$	14.7	0
$\geq 5$	10.8	0

# Interlude

## Inclusive $Z/\gamma^*$ Cross Section :

$$\sigma \times BR(Z / \gamma^* \rightarrow e^+ e^-) = \frac{N - B}{L \times A \times \epsilon_{tot}}$$

- ✓  $N - B$  = from diem invariant mass distribution
- ✓  $L$  = Luminosity (343 pb $^{-1}$ )
- ✓  $A$  = Acceptance
- ✓  $\epsilon_{tot}$  = total efficiency to identify  $e^+ e^-$  pairs from  $Z/\gamma^*$  decays (Trigger, Electron, Track Matching)
  
- ✓  $Z/\gamma^* (\rightarrow e^+ e^-) + \geq n$  jet cross sections ( $n > 0$ ):
- ✓  $N - B$  = from diem invariant mass distribution
- ✓  $L$  = Luminosity (343 pb $^{-1}$ )
- ✓  $A$  = Acceptance
- ✓  $\epsilon_{tot}$  = total efficiency to identify  $e^+ e^-$  pairs from  $Z/\gamma^*$  decays (Trigger, Electron, Track Matching)
- ✓ Multiplicative correction factors to the number of signal events (jet reco/ID, unsmeared, electron-jet-overlap)

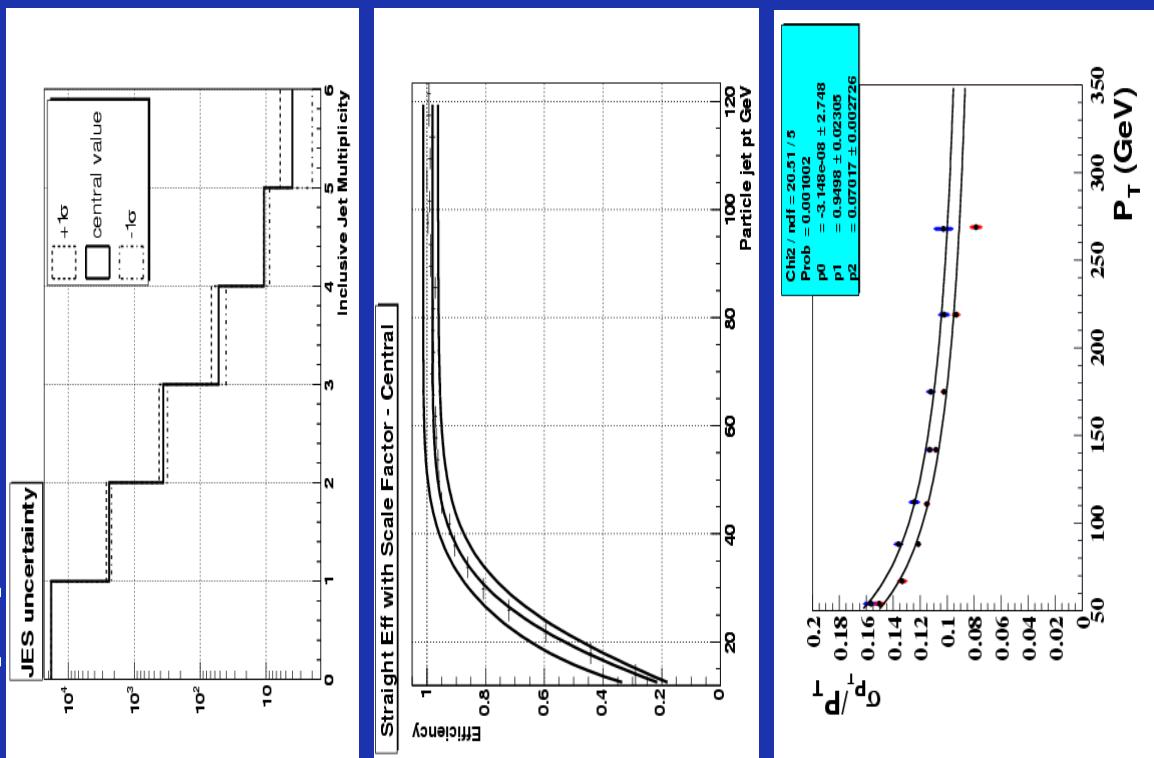




# Systematic Uncertainties

# Systematics (1)

- Jet Energy Scale Uncertainty:
  - JES correction: “calorimeter”  
→ “particle” jets
  - Varying the jet energy scale correction by  $\pm 1\sigma$
  - Rederiving the cross sections
  - Dominant error
- Jet Reco/ID Uncertainty:
  - Rederiving unsmearing and jet reco/ID correction factors based on error bands of efficiency parameterizations
  - Jet energy resolution parameterization



# Systematics (2)

- Electron-Jet-Overlap Uncertainty:
  - Taking the difference between the middle value and corrections derived for  $\Delta R=0.4$  and  $\Delta R=0.7$
- Luminosity Uncertainty:
  - Luminosity is normalized with respect to inelastic cross section
  - The current value of the inelastic cross section was determined at  $\sqrt{s}=1.8\text{TeV}$  and then extrapolated to  $\sqrt{s}=1.96\text{ TeV}$
- Systematic Uncertainty due to trigger, EM, tracking efficiencies:
  - Uncertainties of the object based efficiencies are converted into event based systematic uncertainties
  - Propagated to the cross sections



# Systematics (3): Jet Promotion

- The cross section measurement depends on a precise determination of jet multiplicities
- We study the effect of gaining additional jets from multiple interactions within the same beam crossing: *jet promotion*

Jet multiplicity	Exactly one primary vertex	At least two primary vertices
$\geq 0$	5,900	5,900
$\geq 1$	705	696
$\geq 2$	92	97
$\geq 3$	11	16
$\geq 4$	3	1
$\geq 5$	1	1

Jet multiplicity	Average number of primary vertices
$\geq 1$	$1.583 \pm 0.852$
$\geq 2$	$1.622 \pm 0.911$
$\geq 3$	$1.733 \pm 0.814$
$\geq 4$	$1.4 \pm 0.8$
$\geq 5$	$2.0 \pm 1.0$



# Results and Conclusions

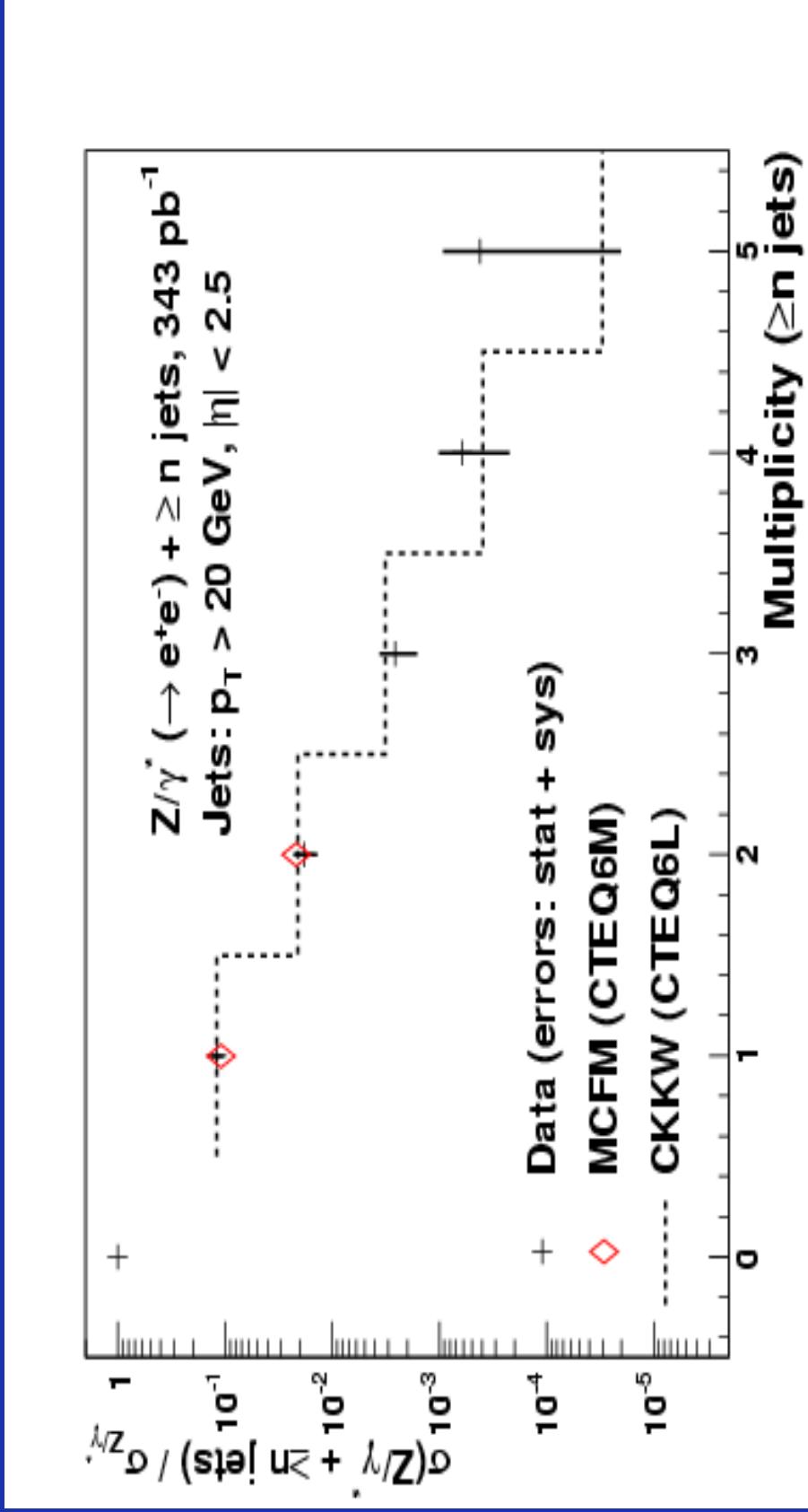
# Z/ $\gamma^*$ ( $\rightarrow e^+e^-$ ) + $\geq n$ Jet Cross Sections

Jet Multiplicity	$Z/\gamma^*(\rightarrow e^+e^-) + \geq n$ Jet Cross Section
$\geq 0$	248.9 pb $\pm 2.5$ (stat) $\pm 16.2$ (lumi)
$\geq 1$	29.6 pb $\pm 0.81$ (stat) $^{+4.3}_{-4.0}$ (sys) $\pm 1.9$ (lumi)
$\geq 2$	4.50 pb $\pm 0.32$ (stat) $^{+1.1}_{-1.1}$ (sys) $\pm 0.29$ (lumi)
$\geq 3$	0.655 pb $\pm 0.13$ (stat) $^{+0.22}_{-0.22}$ (sys) $\pm 0.043$ (lumi)
$\geq 4$	0.151 pb $\pm 0.070$ (stat) $^{+0.072}_{-0.066}$ (sys) $\pm 0.010$ (lumi)
$\geq 5$	0.104 pb $\pm 0.074$ (stat) $^{+0.10}_{-0.06}$ (sys) $\pm 0.0067$ (lumi)

For cross section ratios,  $R_n = \sigma_n/\sigma_0$ , the luminosity measurement uncertainties cancel.



# Cross Section Ratios



Ratios of the  $Z/\gamma^*$  ( $\rightarrow e^+e^-$ ) +  $\geq n$  jet cross sections to the total inclusive  $Z/\gamma^* \rightarrow e^+e^-$  cross sections versus jet multiplicity.

# Conclusions

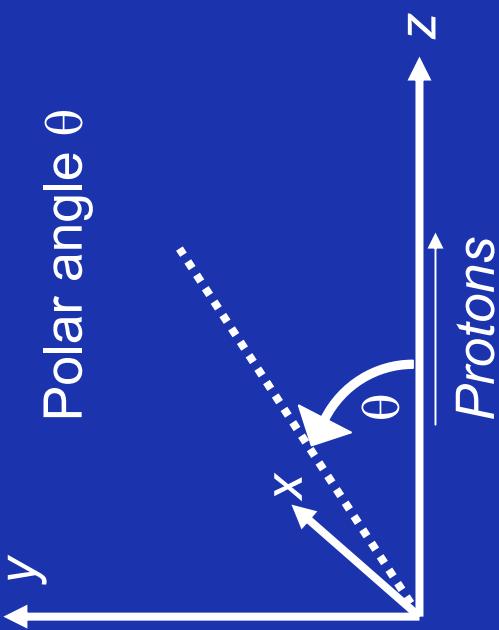
- A study of events with  $Z/\gamma^*$  bosons and hadronic jets in  $p\bar{p}$  collisions at a center of mass energy of 1.96 TeV with the DØ detector has been presented.
- The data sample consists of  $\approx 14,000$   $Z/\gamma^* \rightarrow e^+e^-$  decay candidates from 343 pb<sup>-1</sup> of integrated luminosity.
- Cross sections and jet properties have been measured for jet multiplicities up to 5.
- The results are in good agreement with QCD.





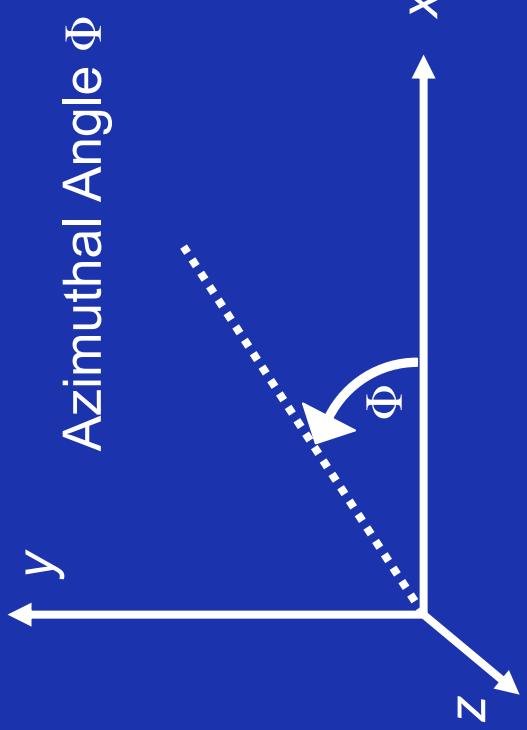
# Backup Slides

# The DØ Coordinate System



$$\eta = -\ln\left(\tan\frac{\theta}{2}\right)$$

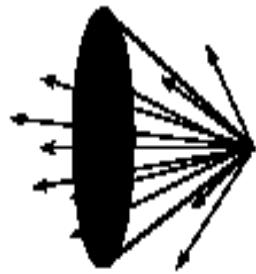
Pseudorapidity  $\eta$



# JES correction



Jet energy scale correction:  
“calorimeter”  $\rightarrow$  “particle” jet



$$E^{true} = \frac{E^{meas} - E_O}{R_{jet} + R_{OOC}}$$

$E^{true}$  “True” Jet Energy; particle level

$E^{meas}$  Measured Jet Energy

$E_O$  Offset (Mult. Int., pile-up, UE)

$R_{jet}$  Calorimeter Jet Response

Measured in situ using  $\gamma$  – Jet  
 $P_T$  balance

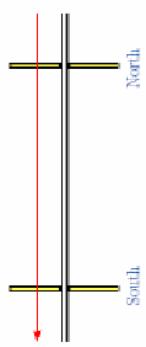
$R_{OOC}$

Out of Cone Calorimeter  
Showering (energy leaking  
in/out of jet cone)

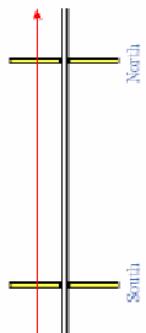
# Luminosity Calculation



Proton Halo



Anti-Proton Halo



Coincidences ( $N^S$ ) are stored in scalers per accelerator tick and Level trigger bit

## Counting Zeros

The average number of interactions per beam crossing,  $\mu$ , is proportional to the luminosity and follows a Poisson distribution. The probability of  $n$  interactions in a given crossing is

$$P(n) = \frac{\mu^n}{n!} e^{-\mu}.$$

The probability of at least one interaction (detector signal) is

$$P(n > 0) = 1 - e^{-\mu}.$$

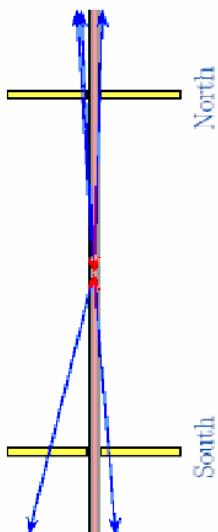
Since  $\mu = \mathcal{L}\sigma_{\text{eff}} / \text{crossing rate}$ ,

$$\mathcal{L} = -\frac{\text{crossing rate}}{\sigma_{\text{eff}}} \ln(1 - P(n > 0))$$

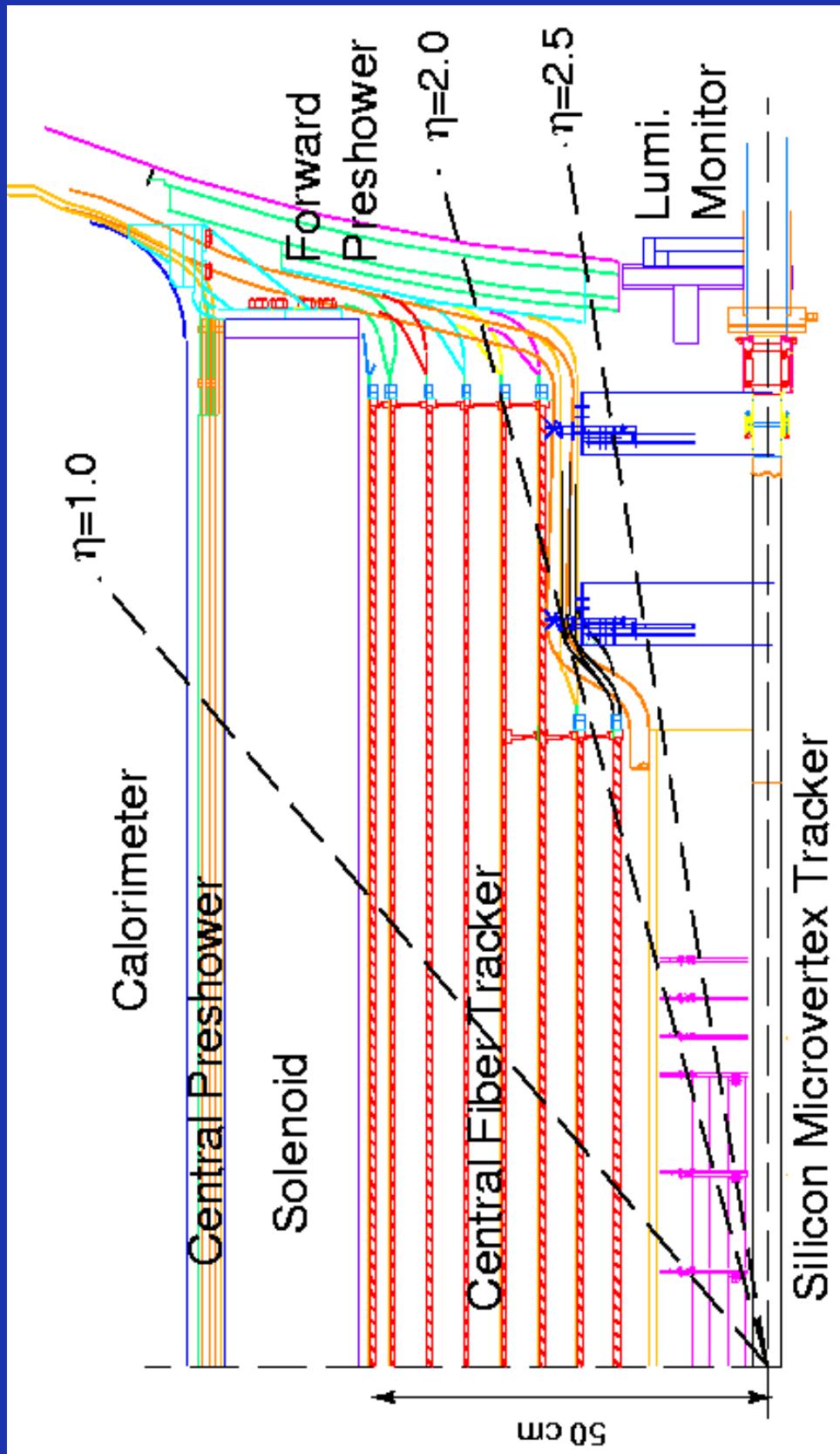
$\sigma_{\text{eff}} = 43\text{mb}$  ( estimate)

Crossing rate = 7.58MHz

## Luminosity (Collisions)



# Inner Tracking Volume



# Calorimeter Segmentation



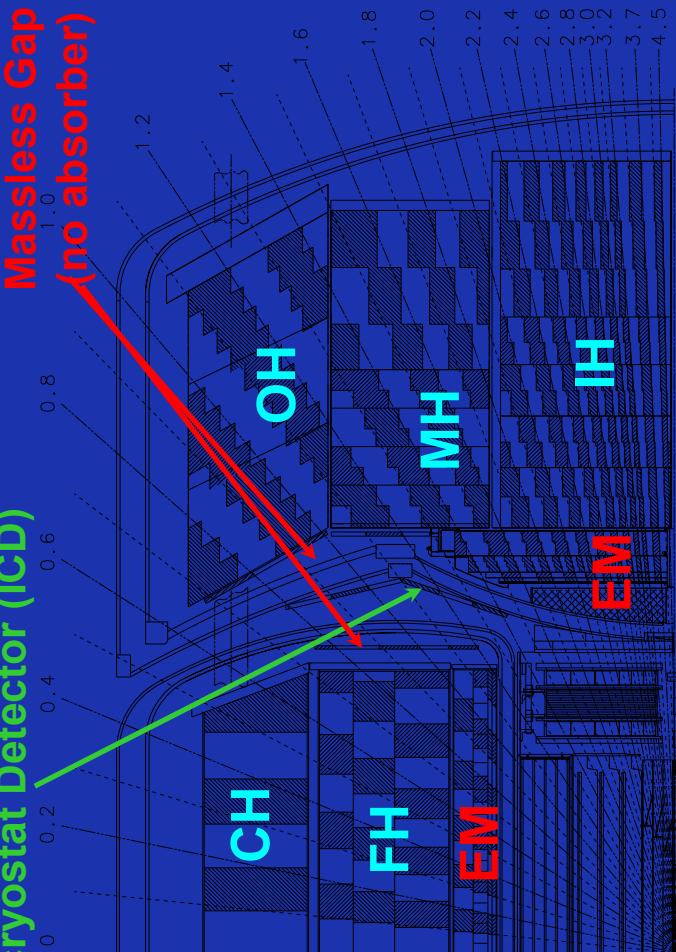
- 50k readout cells ( $<0.1\%$  bad)
- Arranged in semi-projective towers
- Readout cells ganged in layers
- Readout segmented into  $\eta, \phi$  for charge detection

- **Transverse segmentation**

- $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$
- At shower max. (EM3)
- $\Delta\eta \times \Delta\phi = 0.05 \times 0.05$
- 5k semi-projective towers
  - 4 EM, 4-5 Hadronic (fine and coarse) layers
  - Field +2.5 kV ( $E = 11$  kV/cm)
    - drift time  $\sim 450$  ns
  - L1/L2 fast Trigger readout 0.2x0.2 towers

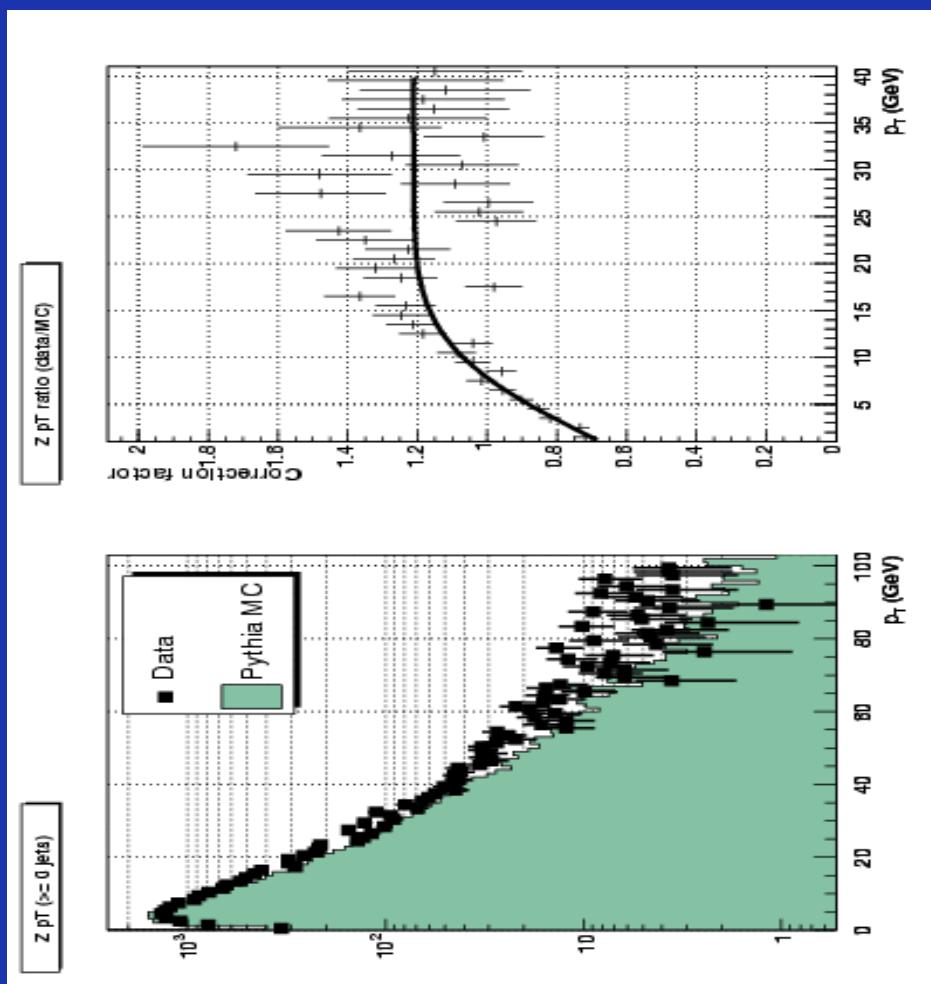
Layer	CC	EC
EM1,2,3,4	$X_0 : 2.2, 7, 10$ 3mm Ur	$X_0 : (0.3), 3, 8, 9$ (1.4mm Fe) 4mm Ur
FH1,2,3,(4)	$\lambda_O : 1.3, 1.0, 0.9$ 6mm Ur	$\lambda_O : 1.3, 1.2, 1.2, 1.2$ 6mm Ur
CH1,(2,3)	$\lambda_O : 3.0$ 46.5mm Cu	$\lambda_O : 3.0, (3.0, 3.0)$ 46.5mm Fe

- **Intercalostat Detector (ICD)**

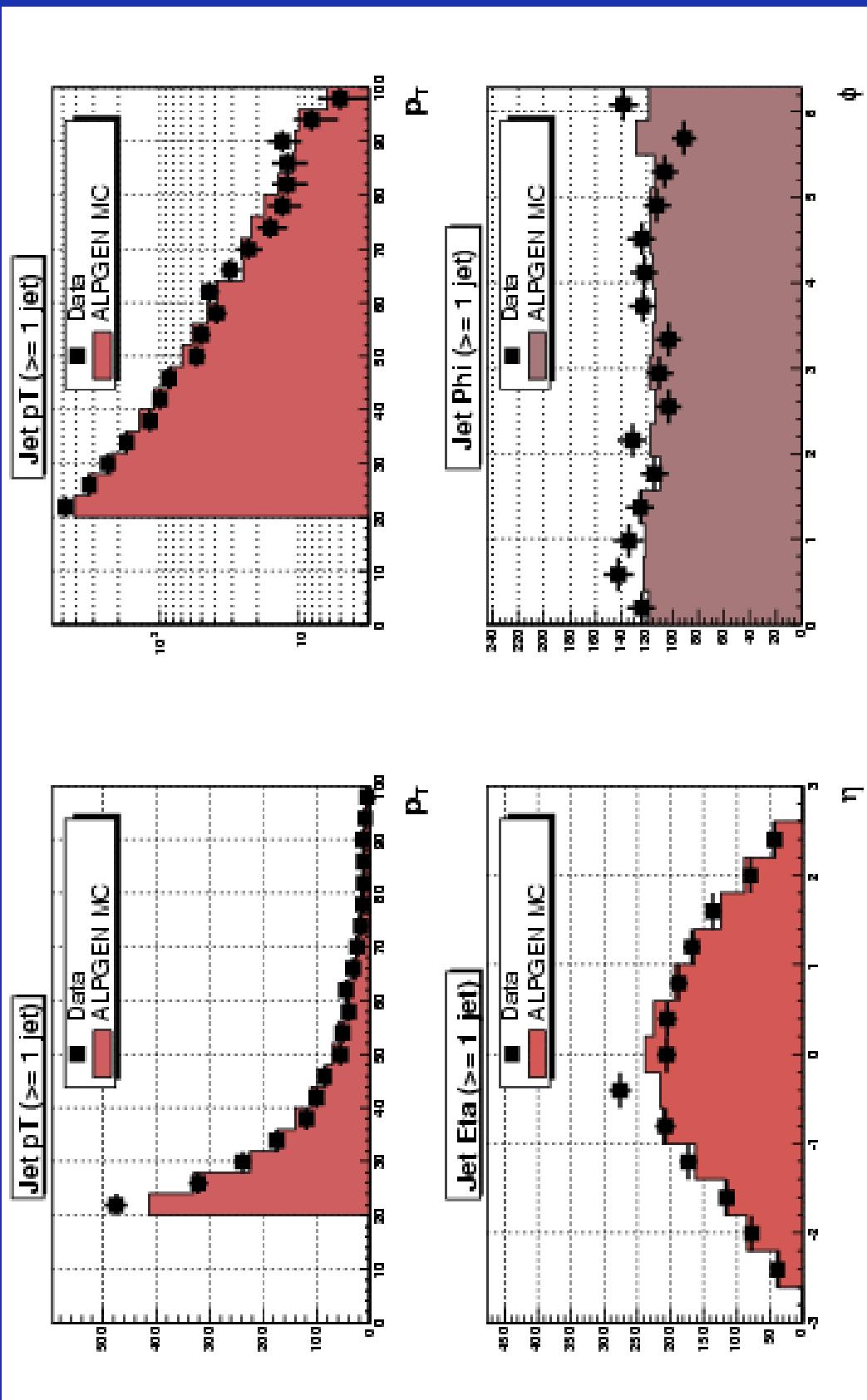


# Z $p_T$ Correction

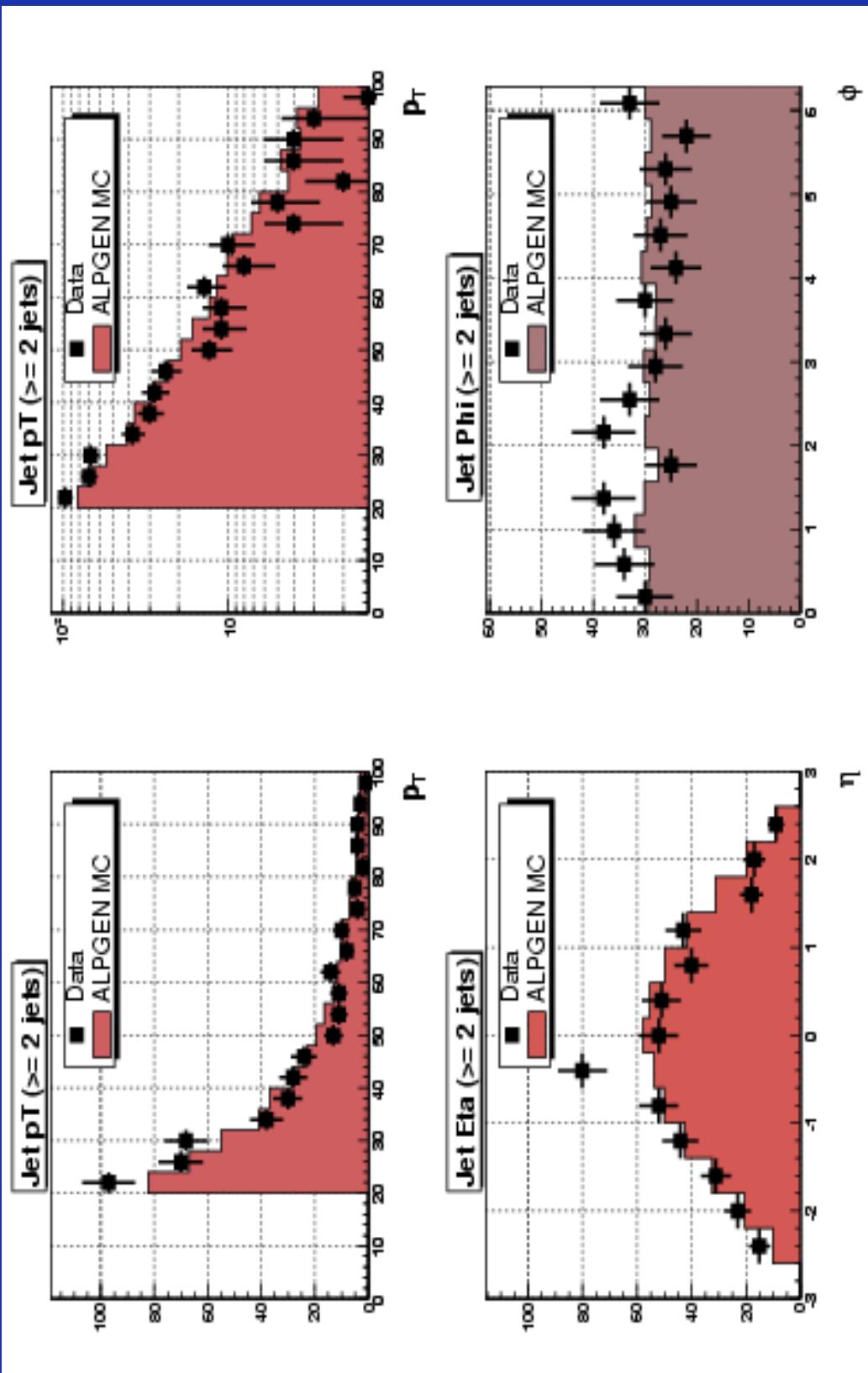
- Comparing Z  $p_T$  in data and PYTHIA MC
- PYTHIA does not fully incorporate higher-order contributions of hard radiation
- Disagreement at high Z  $p_T$
- The ratio of data/MC is applied as an additional correction
- Not needed for ALPGEN + PYTHIA samples



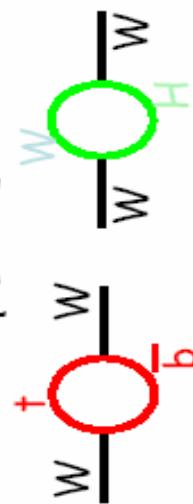
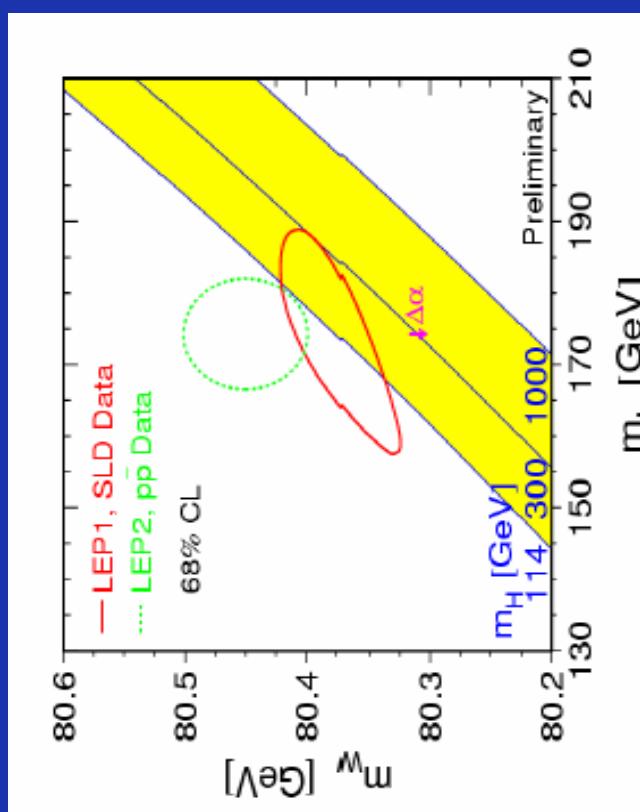
# $Z/\gamma^*$ ( $\rightarrow e^+e^-$ ) + $\geq 1$ Jet Comparisons



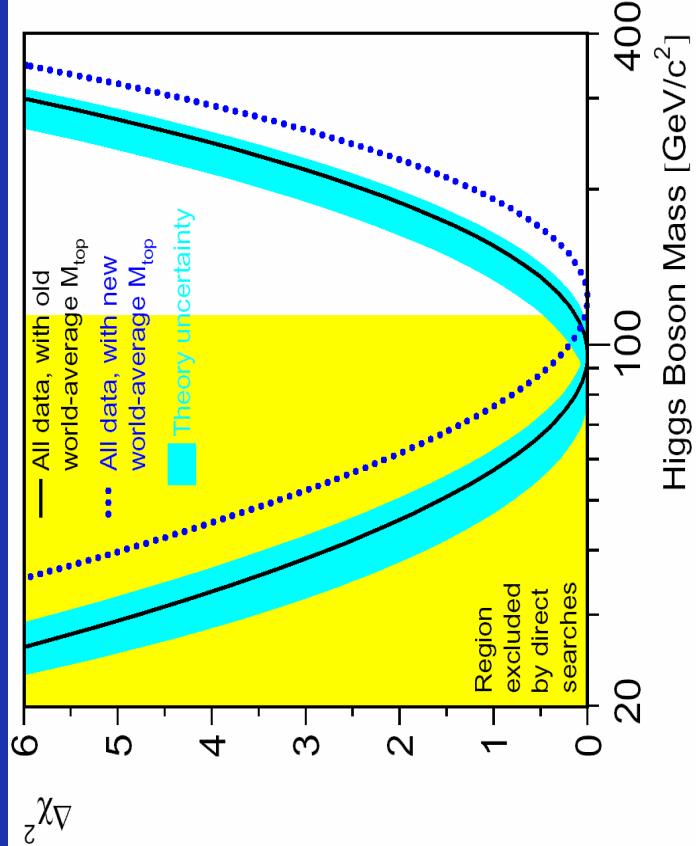
# $Z/\gamma^*$ ( $\rightarrow e^+e^-$ ) + $\geq 2$ Jet Comparisons



# Higgs (1)

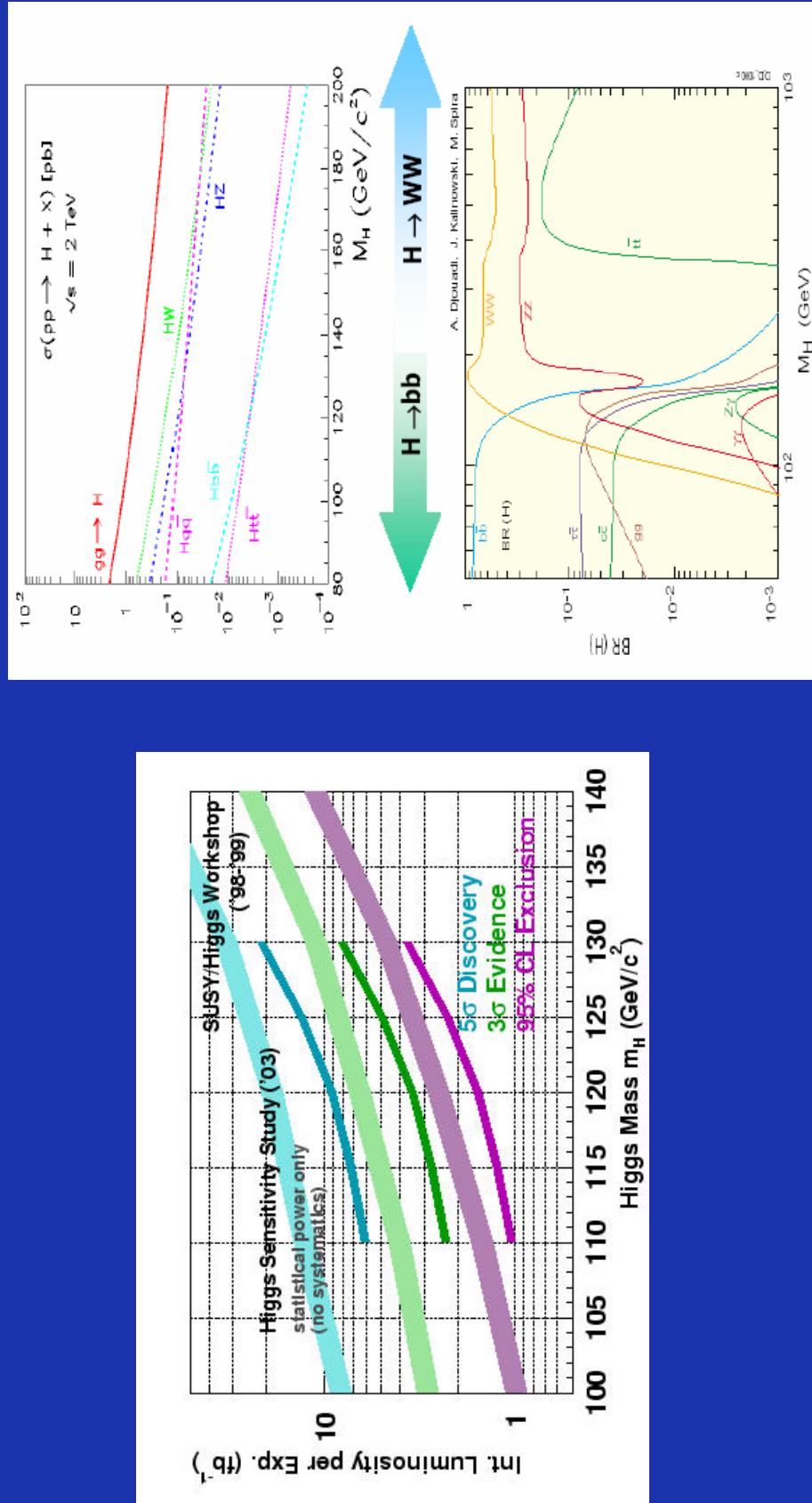


Connection between Higgs and  
EW parameters via higher order  
loop corrections allow estimate  
of  $m_H$ .



- $M_H = 117 \text{ GeV}$ ,
- $M_H < 251 \text{ GeV} @ 95\% \text{CL}$
- LEP's direct search:
  - $M_H > 114.4 \text{ GeV} @ 95\% \text{CL}$

# Higgs (2)



# Large Hadron Collider

- Built at CERN
- Scheduled to start data taking in 2007
- Colliding protons with protons at  $\sqrt{s}=14\text{TeV}$
- ATLAS and CMS multipurpose detectors
- Design lumi is  $10E34\text{cm}^{-2}\text{s}^{-1}$  ( $100\times$  Tevatron)
- $10\text{ fb}^{-1}$  by end of 2008 (?)

